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Sediment properties and depositional environment of the Minnelusa formation (Permo-Pennsylvanian), Northern Black Hills, South Dakota and Wyoming

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SEDIMENT PROPERTIES AND DEPOSITIONAL ENVIRONMENT OF THE MINNELUSA FORMATION (PERMO-PENNSYLVANIAN), NORTHERN BLACK HILLS, SOUTH DAKOTA AND WYOMING

BY

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ABSTRACT

Permo-Pennsylvanian sedimentary rocks of the Minnelusa Formation of the Black Hills uplift, South Dakota and Wyoming, can be divided into upper, middle and lower divisions on the basis of lithology. The upper portion of 150 to 200 feet consists of gray and yellow sandstone, with some carbonates and shales in some sections. The middle portion, about 200 to 220 feet thick consists of gray and red sandstone with carbonate members including the prominent dolomite member at the base; some of the carbonates are cherty. The lower portion, 20 to 60 feet thick, consists of pink sandstone, arenaceous dolomite and thin hard dolomite beds; most sections show evidence of solution, which affects up to 20 feet of the lowermost part of the section.

Sieve analysis shows a gradual upward increase in grain size but with some fluctuations in most of the sections. The other grain size parameters are variable and do not show any trends or correlation. Carbonate cement increases with decrease of grain size suggesting a primary origin. With decrease in grain size a clay and silt-size matrix also becomes increasingly abundant.

The environment of deposition is delineated mainly on vertical grain size variations. Upward increase in grain size is interpreted as indicating a progressively shallowing sea. Composition, sedimentary structures and variation in thickness of bedding were used also, but because these variables were studied in qualitative terms only, their use was limited. The sands are interpreted as being deposited as a transgressive and a regressive sequence due to fluctuation in subsidence and or due to a change in rate of supply. The environment of

deposition includes beaches, offshore bars, and lagoons. Because differences in samples exist almost entirely in the "center" of the frequency curves, and because of the polycyclic nature of the sand, skewness and kurtosis are the least valuable grain size parameters to use in identifying the environment of deposition of this study.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

A. Purpose and Scope of This Investigation

The objectives of this study are: 1) To present stratigraphic details of the Minnelusa Formation in the northern Black Hills where it is better exposed than in the southern Black Hills; and 2) to study the grain size parameters and to relate this to the interpretation of the environment of deposition of this unit.

B. Location and Extent of Area

The Black Hills dome in western South Dakota and northeastern Wyoming is a broad northward trending anticlinal uplift about 100 miles long and 60 miles wide that flanks the Powder River basin on the east and southeast and the Williston basin on the southeast.

Surface sections of the Minnelusa were described and sampled in the northwest and northeast quadrants of the Black Hills (Fig. 1). The location and thickness of each section is given in Table 1.

C. Geological Setting

The Minnelusa Formation lies outside the outer part of the Pahasapa limestone plateau which encircles the central core of the Balck Hills uplift. South and southwest of Sturgis, south and southeast of Crow Peak, and north of Deadwood the outcrop is broad and extends nearly to the summit of Bear Den Mountain; but south of Sturgis it exceeds a width of 2 miles at only few places, and in the zone of steep dips north of Stage Barn Canyon it is less than a mile wide. On the southwest slopeof the Black Hills it is uniformly about 3 miles wide. It is trenched to its base in Sand Creek and Spearfish Canyon.

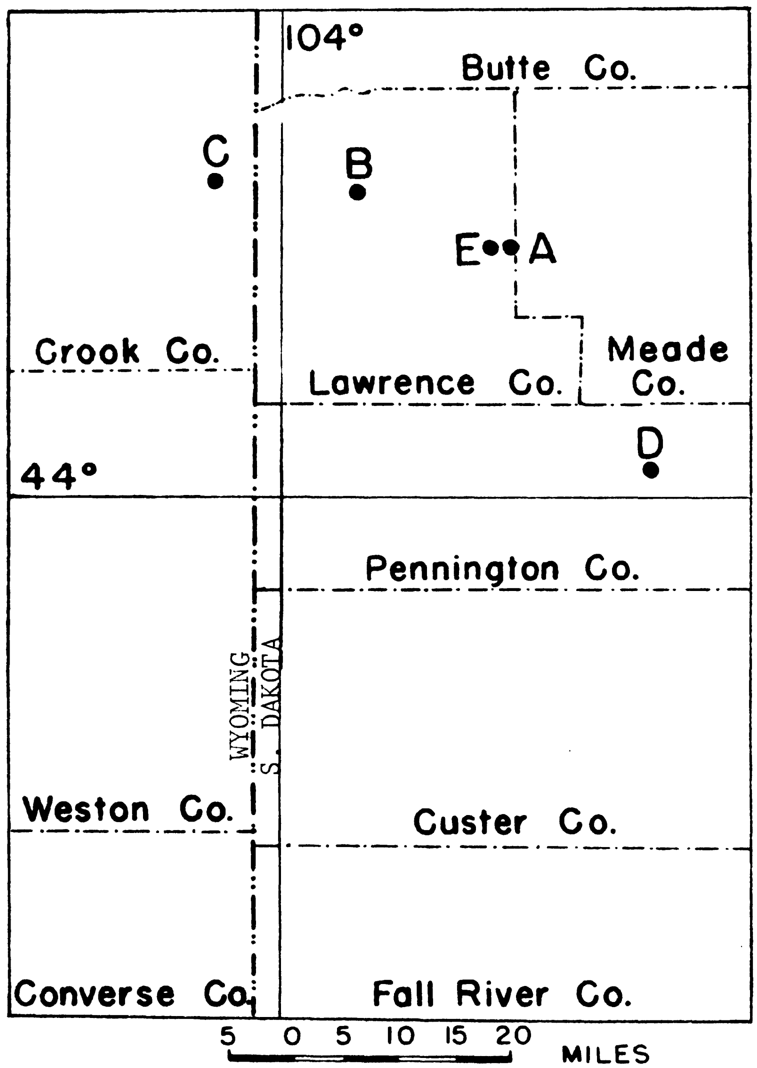

Figure 1. Index Map of the Black Hills, S. Dakota and Wyoming showing location of sections

Table 1. Location and local thickness of stratigraphic sections described and sampled for study.

Section	Section Symbol	Thickness (feet)	Location
Sand Creek	C	398	N 1/2, SE 1/4, SE 1/4, Sec. 13, T. 52N., R. 61W., Tinton 15' Quad. Crook Co., Wyoming
Spearfish Canyon	B	426	NW 1/4, Sec. 27, T. 6N., R. 2E., Spearfish Quad., Lawrence Co., S. Dakota
Boulder Canyon	A	445	NE 1/4, NW 1/4, Sec. 13, T. 5N., R. 4E., Sturgis Quad., Lawrence Co., S. Dakota
Boulder Creek	E	Complete section not measured	SW 1/4, NW 1/4, Sec. 23, T. 5N., R. 4E., Sturgis Quad., Lawrence Co., S. Dakota
Rapid Canyon	D	491	NE 1/4, Sec. 18, SE 1/4, Sec. 7, SW 1/4, Sec. 8, T. 1N., R. 7E. Rapid City West Quad., Pennington Co., S. Dakota

It has been brought to the surface by the Elkhorn, Green Mountain, Inyankara, Bear Butte, Strawberry Mountain and other minor uplifts that lie away from the exposed core area. Figure 2 shows the outcrop of the Minnelusa Formation in the Black Hills region.

The contact between the Minnelusa Formation and the Pahasapa Limestone is usually not marked by any pronounced topographic features but some workers report a disconformity in many places. The lower Minnelusa is thick to massive, with an upward increase in thickness. In the middle part of the section in weathered exposures each younger bed forms a retreating step-like exposure. The upper portion is a massive, cliff-forming persistent unit.

D. Previous Work

The fact that the Minnelusa and its equivalents in Wyoming contain the most important oil producing zones in the Powder River basin has stimulated many studies of these rocks in Wyoming and adjacent areas including the Black Hills, both in outcrop and well sections. This has resulted in considerable accumulation of data on the stratigraphic setting, but there are no laboratory investigations on this formation, at least in the Black Hills uplift, which have been previously reported. Most of the detailed stratigraphic work is in unpublished theses except that Brady (1931) published his observations of the Minnelusa near Beulah, Wyoming. Although attempts at regional synthesis and correlation are acknowledged throughout the text and in the references, it seems appropriate to mention major contributions here separately. Darton (1904, 1925) assigned the Minnelusa Formation to the Pennsylvanian system and attempted regional correlations. Condra *et al*. (1940)

Figure 2. Areal extent of the Minnelusa Formation in the Black Hills uplift, South Dakota and Wyoming, modified from P.M. Work (1931)

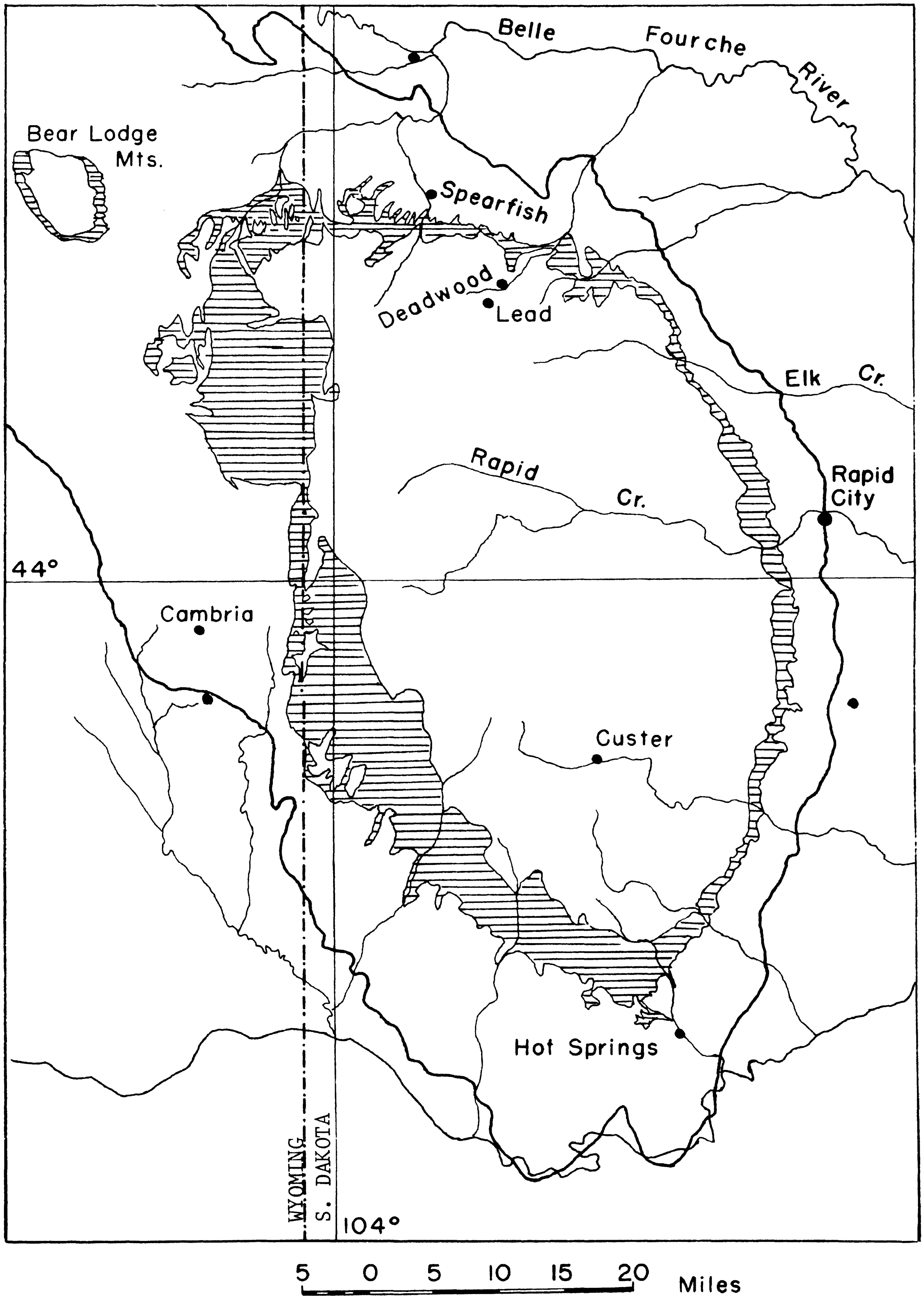
Belle
Fourche
River
Bear Lodge
Mts.
Spearfish
Deadwood
Lead
Elk
Cr.
Rapid
Cr.
Rapid
City
44°
Cambria
Custer
Hot Springs
WYOMING
S. DAKOTA
104°
5 0 5 10 15 20 Miles

Figure 2

provided a detailed description of the Hot Springs area outcrops, in a regional correlation of their zonation, to the Hartville uplift. Thompson and Kirby (1940) constructed a cross-section between Colorado Springs and the Black Hills; Bates (1955) studied the Permo-Pennsylvanian relationships in the area from Laramie to the Black Hills area. Wilson (1962) published isopach-lithofacies and paleogeographic maps of the Minnelusa and its equivalents in the Powder River basin and the adjacent areas.

II. STRATIGRAPHY

A. General Stratigraphy of the Black Hills

The Black Hills uplift is an eroded asymmetrical elongated dome, whose exposed rocks are largely older and therefore stratigraphically below those that form the surface of the adjoining plains.

For general orientation, the stratigraphic section of the northern Black Hills, where the studied stratigraphic sections are located, is given in Figure 3. Only the stratigraphy of the Minnelusa is discussed here.

B. Stratigraphy of Minnelusa Formation

1. Nomenclature

Collectively, the strata lying above the Pahasapa and below the middle Permian Opeche Shale in the Black Hills area of western South Dakota and eastern Wyoming belong to the Minnelusa Formation. The term "Minnelusa" was first applied by N.H. Winchell in 1875 to a portion of the bright-colored members of the Carboniferous lying above the gray Pahasapa Limestone. Darton (1901) used the name to designate all sandstones and limestones in the Black Hills region lying between the Pahasapa Limestone below and the Opeche Formation above. "Minnelusa" is the Dakota Indian name for Rapid Creek (Pennington County, S. Dakota) and the Rapid Creek exposures have been commonly regarded as the type section.

Wilson (1962), in studying the Powder River basin and adjacent sections, raised the term "Minnelusa" to group status and included the Tensleep, Amsden and Sacajawea Formations. Moore (1970), in the Powder River basin, agreed with Wilson in elevating the term "Minnelusa" to

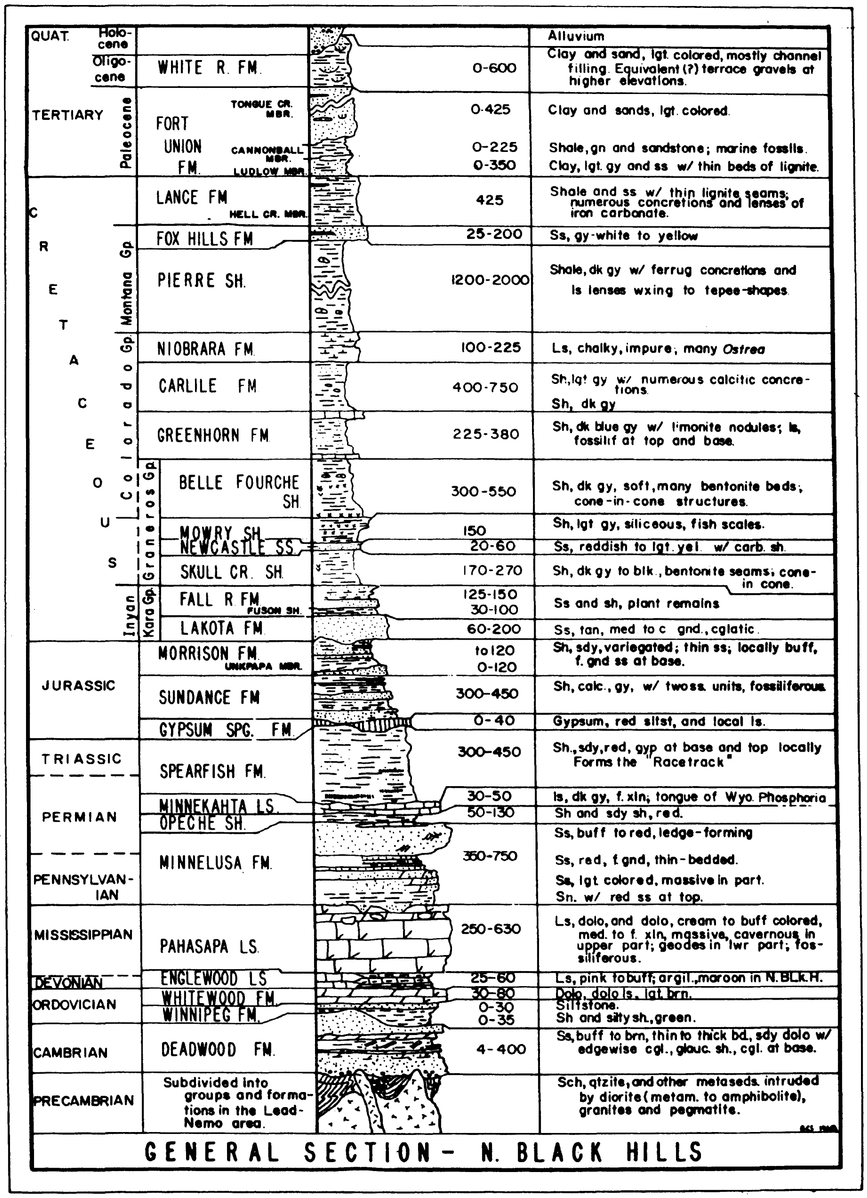

Figure 3. Generalized stratigraphic column of northern Black Hills compiled by A.C. Spreng, University of Missouri-Rolla, 1968

group status, but disagreed with the subdivision of formations for reasons explained later in this thesis. He suggested the terms Casper and Hartville Formations instead, altering the nomenclature of Wilson, at least for the Powder River basin.

The older usage of Darton is used herein and the whole sequence is referred to the Minnelusa Formation.

2. Lithologic Character

The Minnelusa outcrops of the northern Black Hills consist predominantly of sandstones with carbonate and shale facies occurring mainly in the lower and middle beds. However, Bates (1955) reported that the formation in the type area in Rapid Creek Canyon contains only about 58 percent sandstones, and the subsurface sections contain even lower proportions. The lower contact of the formation is obscured by a covered interval in all of the studied sections except in the Boulder Creek and Boulder Canyon sections where the Pahasapa Limestone underlies the Minnelusa unconformably. Work by others, Agatston (1954) and Mallory (1967) in Wyoming and Wilson (1962) in the Powder River basin, Wyoming and adjacent areas including the Black Hills, indicates that the sequence overlies the Pahasapa Limestone or its equivalents with "a marked disconformity." Dunbar and Rodgers (1957, p. 120) record,

> "...where exposed again in the rim of the Black Hills a hundred miles farther northeast, the basal Pennsylvanian beds are light-gray limestone resting paraconformably on the lower Mississippian limestones, and the contact is inconspicuous in most outcrops although more than half a geologic period is unrecorded, yet the hiatus is even greater here than in the Hartville uplift."

The upper limit of the formation is commonly marked in the western Black Hills uplift by a transition to the marine limestone and dolomites of the Phosphoria Formation. This transition is best seen in the Sand Creek section. In the eastern flanks of the Black Hills, the Minnelusa is overlain unconformably by the red shales and siltstones of the Opeche Formation.

In the area of study, the Minnelusa Formation has been divided into three units totaling 398 to 491 feet in thickness (Fig. 4). The units correspond closely to Wilson's (1962) divisions.

An upper portion of about 150-200 feet, equivalent to the Tensleep Formation of Wilson, and Casper Formation of Moore (1970), is characteristically quartzose, buff to gray, with yellowish brown speckling believed to be due to limonite staining. The sandstone is fine-grained, well to very well sorted, subangular, translucent and pitted, with a very small ratio of larger grains very well rounded and frosted. It is calcareous to non-calcareous but friable, except when it is siliceous. Individual sandstone units are locally silica cemented, and in some cases silica comprises the bonding material for the entire sand portion of the sequence, for example, the Boulder Canyon and Spearfish Canyon sections. Most beds show cross-bedding which generally dips to the southwest. The beds are massive, forming cliffs. There is little or no carbonate or shale in this portion of the studied sections except in the Rapid Canyon section where there is a considerable interval of impure dolomite and dark gray shale.

Bates (1955) reported that in the subsurface sections are gypsiferous. On the outcrop gypsiferous sections are marked by numerous collapse structures and breccias. This characteristic is represented in the Rapid Canyon section (unit 12, Fig. 5) and Sand Creek section

Figure 4. Condensed sections showing the lower, middle and upper divisions of the Minnelusa. Top of Minnelusa is taken as a horizontal datum

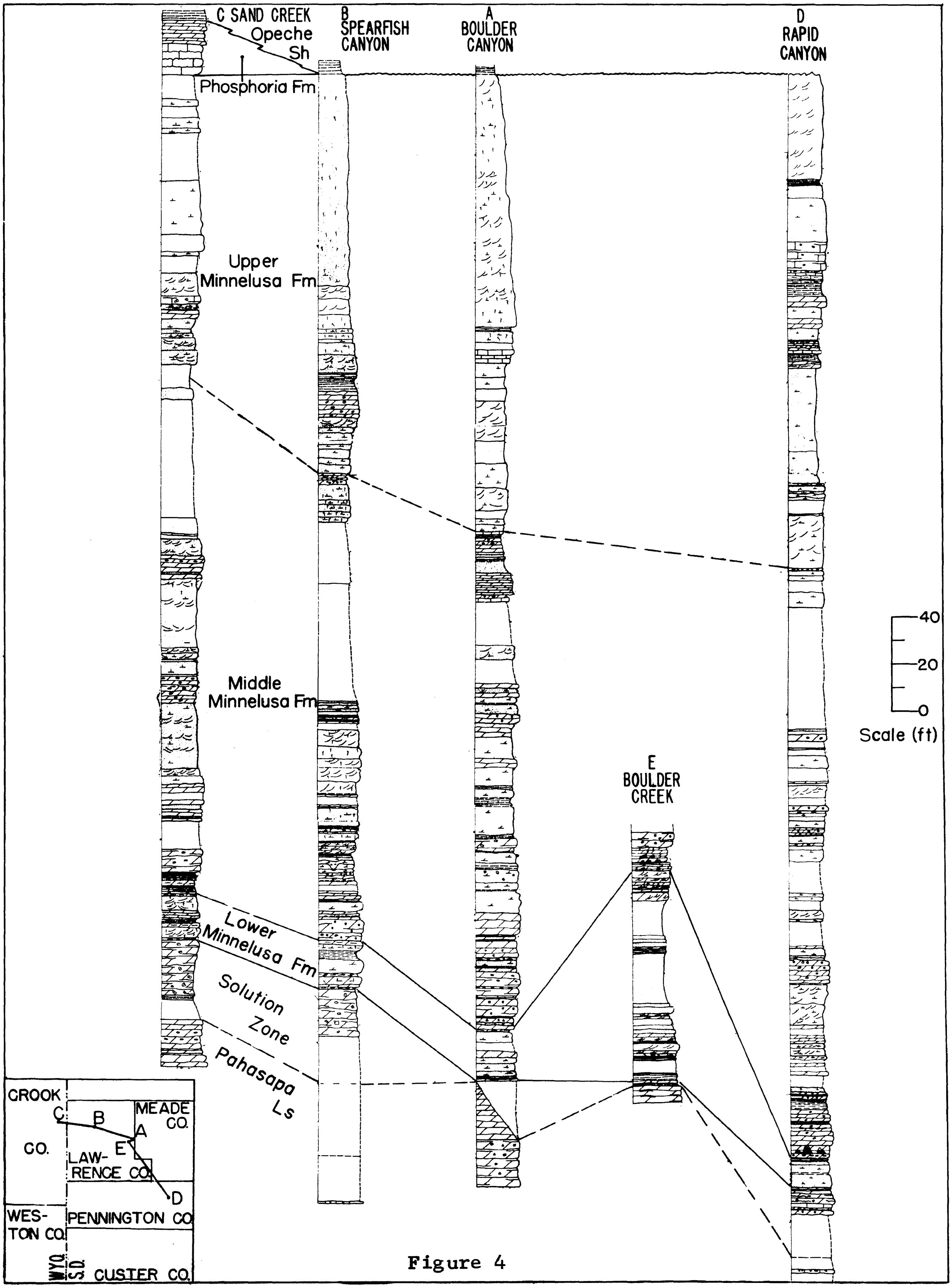
C SAND CREEK
B SPEARFISH CANYON
A BOULDER CANYON
D RAPID CANYON
E BOULDER CREEK
Opeche Sh
Phosphoria Fm
Upper Minnelusa Fm
Middle Minnelusa Fm
Lower Minnelusa Fm
Solution Zone
Pahasapa Ls
40
20
0
Scale (ft)
CROOK CO.
MEADE CO.
LAWRENCE CO.
WESTON CO.
PENNINGTON CO.
CUSTER CO.
WYO.
S.D.

Figure 4

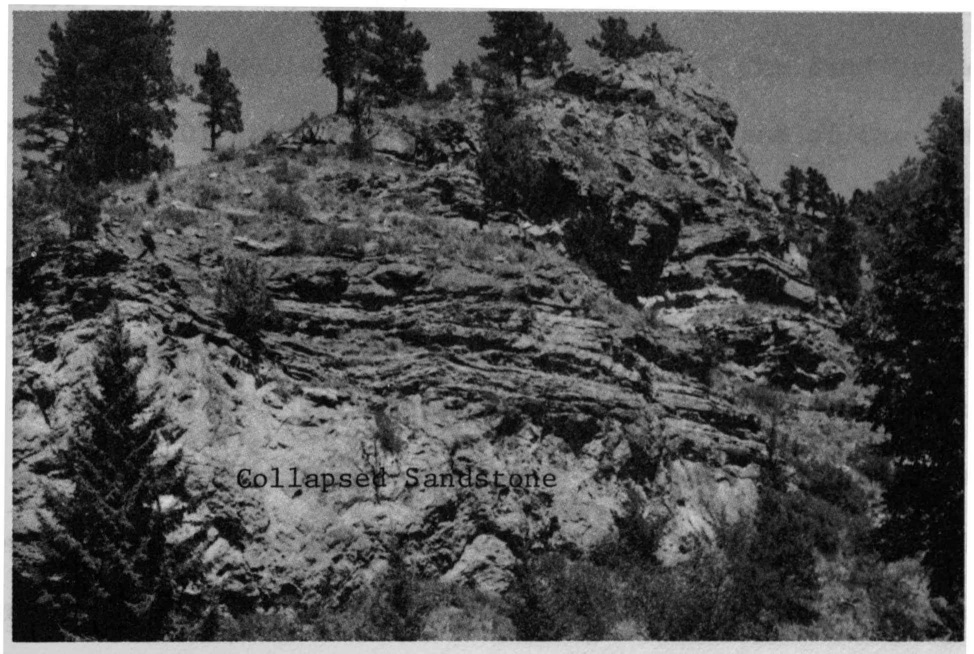

Figure 5. Photograph shows the collapsed sandstone in the upper Minnelusa Formation at Rapid Canyon Pennington Co., S. Dakota

(unit 4) by collapsed sandstones consisting of coarse blocks of sandstone, dolomite and limestone cemented by a fine calcareous sandstone. No evidence of these breccias is seen in the Boulder Canyon section, although the whole sequence is well exposed. The breccias are interpreted by Bates (1955) as being produced in place, by removal of anhydrite and break-up and reworking of the associated beds. Brady (1931) reported finding gypsum horizons together with limestone and shale beds near Beulah, Wyoming, northeast of the Sand Creek section. Moore (1970) at Buch Ranch, on the north flank of the Black Hills found that the interval is composed almost entirely of gypsum with some scattered sandstones and thin dolomites.

The middle Minnelusa Formation (Fig. 6A,B) about 200-220 feet thick (correlative with Wilson's Amsden), consists of alternating carbonate and sandstone members interbedded occasionally with shale. Sandstones still predominate, however. The carbonates are mainly dolomites, dense to fine-grained, gray, normally pitted and nearly everywhere thick-bedded or massive, with vugs lined with calcite crystals. The vugginess is possibly due to the solution of fossils. In most of the sections there are three fossiliferous horizons (mostly indistinct molds and casts). The lowest of these is at the base of this middle division (Fig. 7). This horizon is well-defined throughout all the sections and can be traced from one section to another and used as a key for correlation. It is probably the equivalent of Division I of the Hartville Formation, Condra, Reed & Scherer (1940). It contains molds of pelecypods, crinoid columnals, brachipods and bryozoans. In this horizon, there are tentatively identified algal

Figure 6A. Photograph of the lower and middle Minnelusa Formation at Sand Creek, Crook Co., Wyoming, showing the massive and ledge-forming character of the middle portion of the sequence

Figure 6B. Photograph of the lower and most of the middle of Minnelusa Formation at Rapid Canyon, Pennington Co., South Dakota, showing again the massive and and ledge-forming character of the middle portion of the sequence

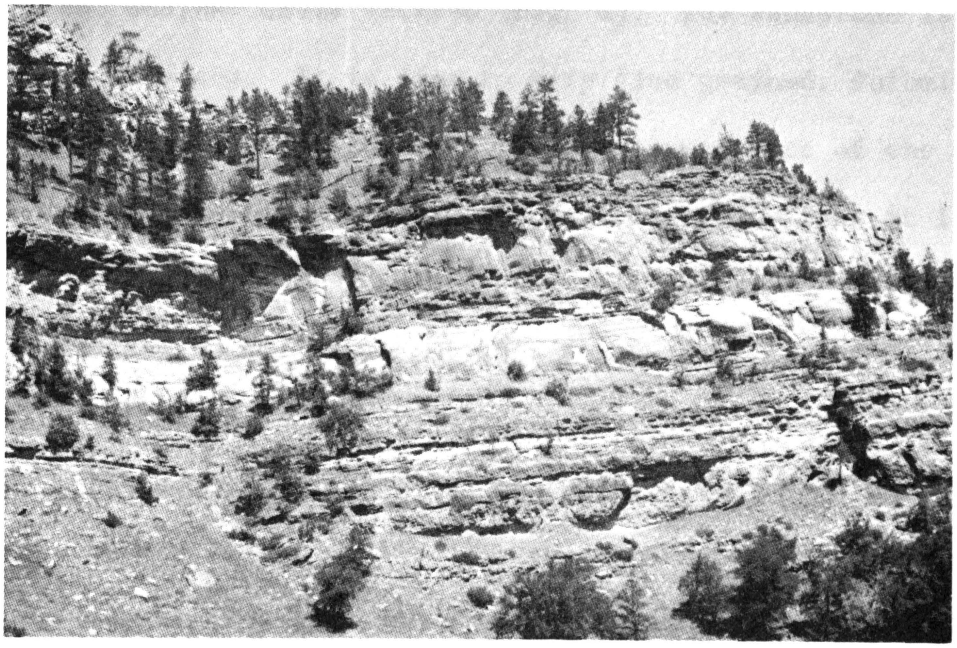

Figure 6A

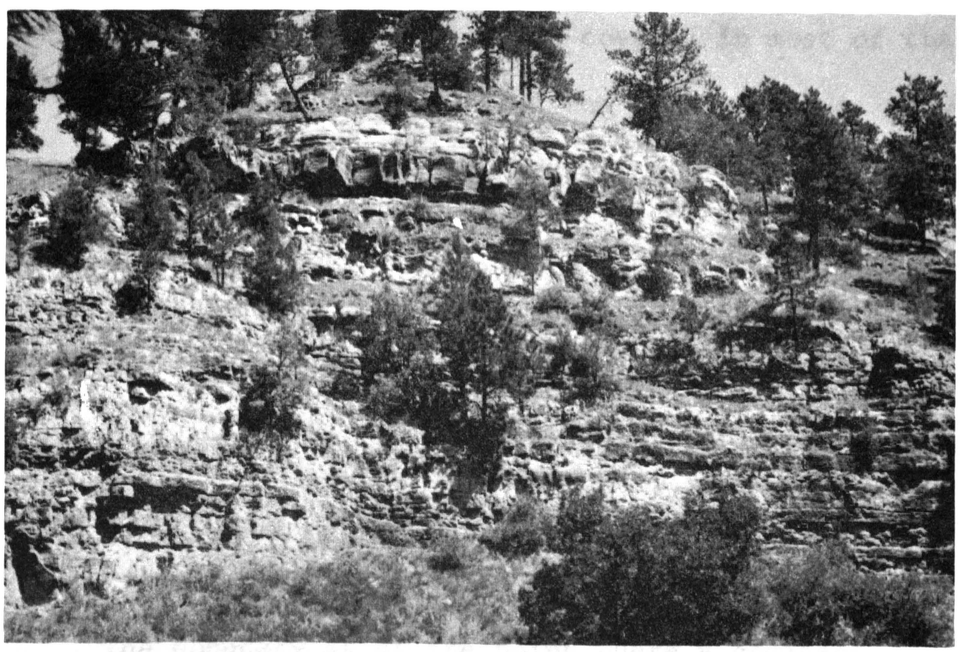

Figure 6B

mounds in all of the sections and a definite stromatolitic reef (LLH type) in the Boulder Creek section (Fig. 8). The sandstone is pink, and red near the top. It is fine to very fine grained, dolomitic or calacreous with less silt and clay than the lower part of the sequence, friable to well indurated and massive, although sometimes it is medium to thick-bedded and ledge-forming. The unit is cross-bedded with dips again to the southwest; ripple marks are occasionally found. The weathered surface is knobby, giving the sandstone a very distinctive feature. This bumpy character is possibly due to the fact that the calcareous cement is not evenly distributed and trends to consolidate around points, binding the sand together in spherical masses which are more resistant than the rest (Boardman, 1942, p. 66). The red bed at the top of this portion of the formation in the Rapid Canyon section is not seen in the other sections, but this is may be due to the fact that the equivalent horizon is covered in most of the sections. However, in the Boulder Canyon section the whole sequence is well exposed, but no red beds are present there. Local changes are common, variations often occur in short distances from the sites selected for description. The contact with the upper portion is indefinite and gradational, but some workers (Love, 1939; Baker, 1946; Branson and Branson, 1941; and Wilson, 1962) report disconformities in some places. Herein, the boundary between the lower and middle portions is placed in accord with Wilson (1962, p. 123):

> "The boundary is at the point where a dominant Tensleep gives way to a dominant Amsden one. In most sections, this coincides with the boundary separating a predominance of sandstone above from that of carbonates or shale below. In isolated instances where the Amsden may also consist

Figure 7. Photograph showing the lowest limestone horizon of the middle Minnelusa at the Boulder Creek locality in Lawrence County, South Dakota

Figure 8. Photograph showing linked algal mounds of the LLH type, which only one of the mounds shown here

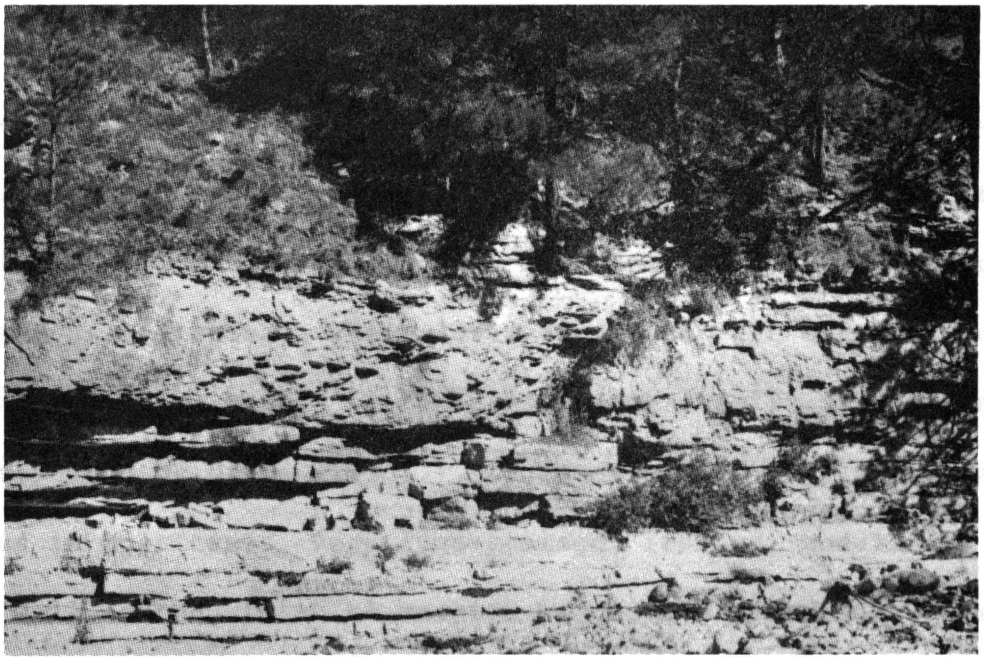

Figure 7.

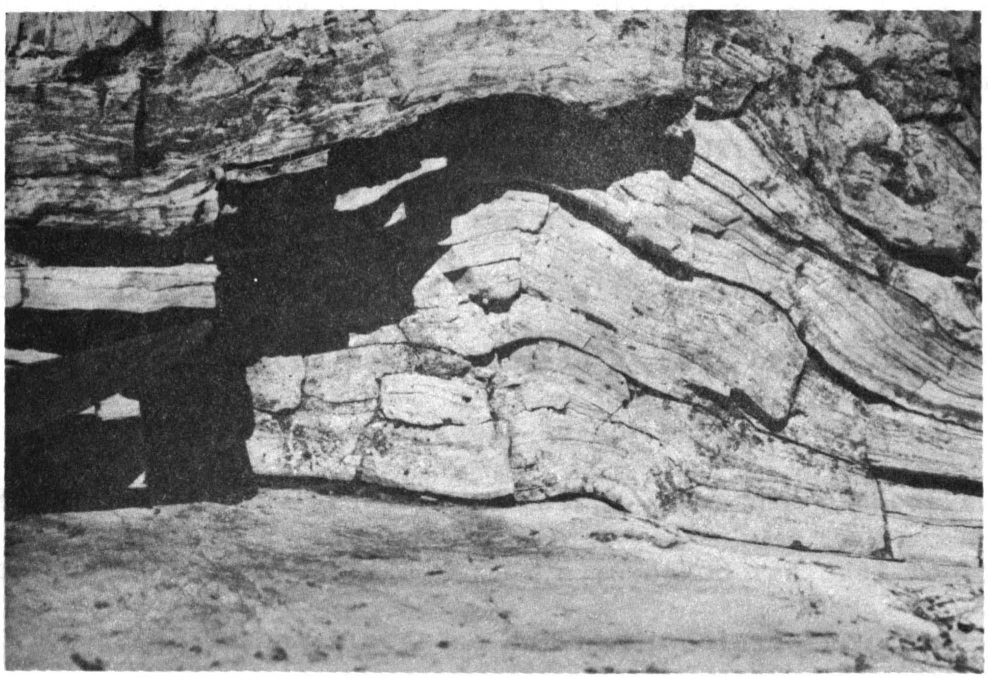

Figure 8.

> largely of sandstone, the selection is made where most of the sand loses its buff or gray Tensleep color and acquires an Amsden red. Similar adjustments to detail may be made in other peculiar instances."

The lower portion is a persistent unit, 20-40 feet thick over all the studied sections and probably in the entire Black Hills. It consists of pink dolomitic sandstone to arenaceous dolomite and red shale and micaceous siltstone. These lower sandstones are interbedded with hard, thin dolomite beds. It contains marine fossils of Desmoinesian age as reported by Dille (1930). The sandstone is very silty and micaceous in most cases, very fine-grained, frosted, moderately well to very well sorted, thick to massive bedded and sometimes cross-bedded although the cross-bedding is not well defined. The sandstones are hard, very well indurated, and siliceous in some places as in the Sand Creek and Boulder Creek sections. This portion of the section is likely the correlative of Division VI of Condra, Reed & Scherer (1940) Hartville Formation which, in turn, is the Sacajawea of Wilson.

Beneath this lower portion, there is a solution zone (see Fig. 4, p. 13) 0-20 feet thick in most of the sections, consisting of impure, brecciated, sandy dolomite (Fig. 9A,B), with residual chert and soft shale. This solution zone was overlooked by most of the workers or was put into the Pahasapa Limestone. This author believes this unit represents either leached and weathered Pahasapa Limestone without transportation of the Pahasapa fragments or a reworked residual mantle derived from the Pahasapa Limestone during Minnelusa time; therefore he places it in the Minnelusa Formation.

Previous work indicates that the formation thickens toward the south and southwest. The subsurface sections are much thicker than

Figure 9A. Photograph showing the solution zone beneath the lower Minnelusa at Sand Creek, Crook Co., Wyoming

Figure 9B. Photograph showing the solution zone beneath the lower Minnelusa at Spearfish Canyon, Lawrence Co., South Dakota

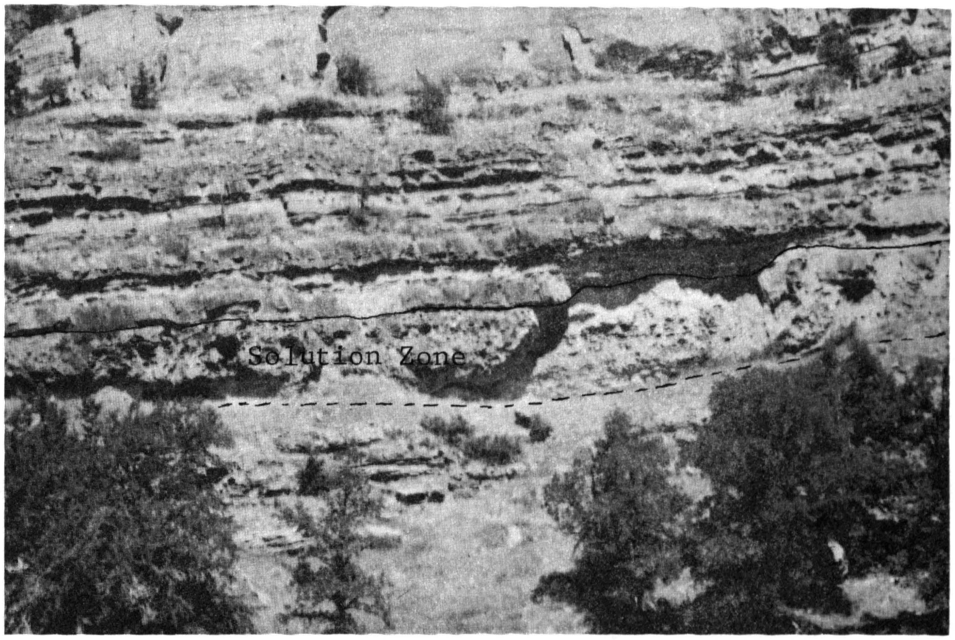

Figure 9A

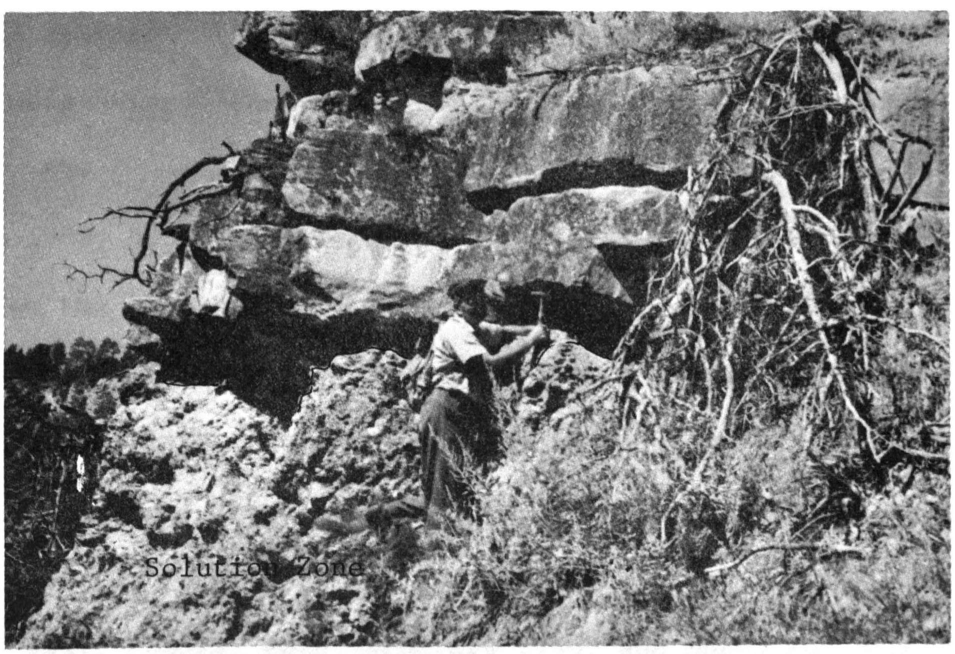

Figure 9B

those at the surface. Local change in thickness are possibly due to one or all of the following causes: 1) the difference exerted by the topography of the post-Pahasapa erosion surface. That erosion is irregular and produced appreciable relief, thus affecting the accumulation of the overlying sediments, 2) leaching of the anhydrite from the surface sections. Baker (1947) stated that the extensive solution of carbonate and calcium sulphate has resulted in thinning of "about 200 feet or more" or, 3) southward thickening of the carbonate-shale sequence of the lower part of the formation (basinward). To the north of the Black Hills, the Minnelusa thins and becomes a dominantly clastic section as the Charles Formation (post-Madison, Mississippian) intervenes above the Pahasapa or Madison.

In the Minnelusa Formation cross-bedding and channeling are common although the cross-bedding in the upper and lower portions is generally not well defined. Cross-bedding, which dips mostly southwest, commonly occurs wedge-shaped sets (Fig. 10A, B).

3. Age

In 1909, Darton tenatively assigned the Minnelusa to the Pennsylvanian on the basis of molluscan remains found in its upper beds in the southern Black Hills, and by 1925 Darton definitely considered it to be Pennsylvanian. Dille (1930) identified a number of fossils from the basal red shale near Loring Siding (southern Black Hills) and concluded that the basal beds are Desmoinesian in age. Other authors (Brady, 1931; Condra, Reed, Scherer, 1940; and Moore and others, 1944) considered that most of the Minnelusa was Pennsylvanian by lithologic correlation with the Hartville Formation and the Mid-continent regions.

Figure 10A. Photograph showing wedge-shaped cross-bedding in u. Minnelusa at Spearfish Canyon, Lawrence Co., South Dakota

Figure 10B. Photograph showing wedge-shaped cross-bedding in l. Minnelusa at Sand Creek, Lawrence Co., South Dakota

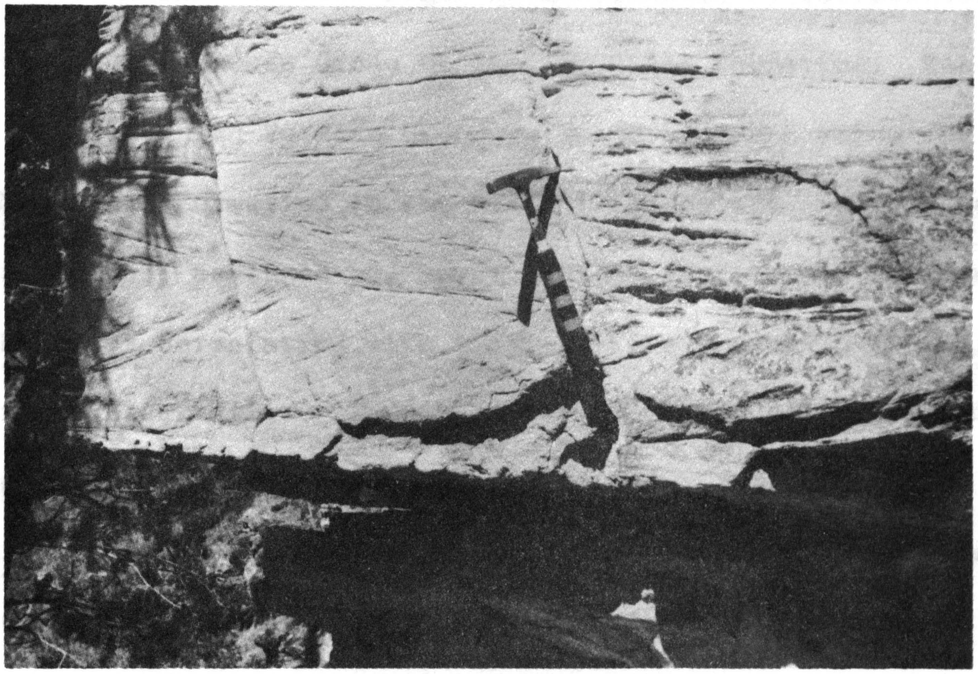

Figure 10A

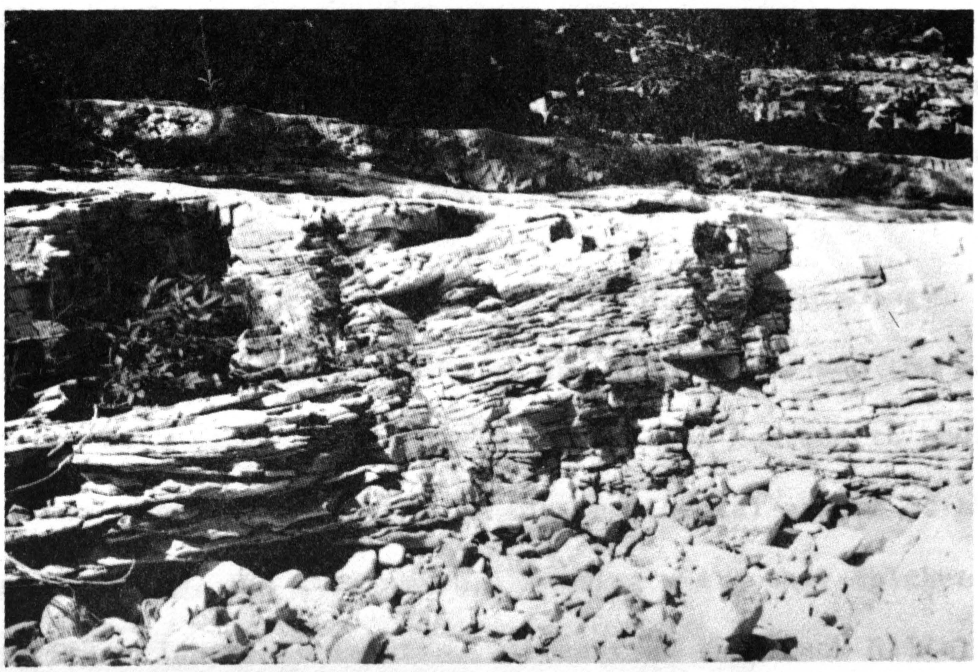

Figure 10B

Condra and others (1940), Thompson and Kirby (1940), suggested that the uppermost Minnelusa beds might be Wolfcampian by correlation with the Brook Creek and Casa Group of the Hartville Formation. Reed (1955) put the Pennsylvanian-Permian boundary about 150 feet below the top of the Minnelusa Formation in the Black Hills uplift. Love, Henbest, and Denson (1953) assigned the upper 250-300 feet to the Permian system on the basis of correlation with the Hartville Formation (Division I) south of the Black Hills. The remainder of the Minnelusa is considered to be Pennsylvanian in age. Jennings (1959), working in the northern Black Hills, placed the contact between the Pennsylvanian and Permian at the top of the lower carbonate sequence about 125 feet above the base on the basis of a fusulind zone containing a species of *Triticites*. Verville and Thompson (1963) described Virgilian forms of *Triticites* collected 250 feet below the top of the Minnelusa in the northern Black Hills.

Thus, from the above data one can, at the present, assign a Pennsylvanian (Demoinesian) to L. Permian (Wolfcampian) age to the Minnelusa Formation.

4. Regional Trends and Lateral Extension of Terminology

The Permo-Pennsylvanian rocks of the Black Hills and the adjacent areas (from their northern truncation in central Montana to southern Wyoming where they interfinger with the continental arkose of the Fountain Formation, and from western Wyoming where they thicken into the Wells Formation to at least as far east as the Black Hills) show close lithologic similarities. The names applied to them vary from one place to another and include Tensleep, Amsden, Quadrant, Minnelusa, Hartville, Casper, Ingleside and Fountain Formations (Fig. 11). Wilson (1962) noticed that the use of the many names complicated the stratigraphic picture. On the basis of lithology and lateral continuity of these units, he classified all the Permo-Pennsylvanian rocks into three formations: 1) and upper sandstone sequence - the Tensleep, 2) a middle carbonate, shale and sandstone - the Amsden and 3) a lower clastic portion - the Sacajawea. On this basis, Wilson suggests eliminating all the other names and replacing them by the name Minnelusa. The term Minnelusa would be raised to group status and would include the Tensleep, Amsden, and Sacajawea Formations.

But Moore (1970, p. 19) criticized Wilson's classification. He stated that:

> "The Tensleep Formation was named on the western flank of the Bighorn Mountains for sandstone and carbonates of Pennsylvanian age. This name should not be used for rocks of Permian age on the eastern flank of the Bighorn Mountains that were deposited in a different depositional basin. The type section of this upper sandstone interval in the Powder River basin is on the east end of Casper Mountains and so should be known as the Casper Formation.
>
> The terms Amsden and Sacajawea should also be disregarded as formational names. Neither of these units have been defined in the Powder River basin, and their use is discouraged. According to Strickland (1957) the term Sacajawea should be restricted to Mississippian sediments below the Darwin. The most complete marine Pennsylvanian section is exposed in the Hartville region (Verville and Thompson, 1963), so the lower portion of the Minnelusa Group should be known as the Hartville Formation. This unit could be subdivided if necessary, but it should not be separated into multiple, thin units which cannot be traced on lithologic basis."

Moore suggested that two member names be assigned to rocks of Missourian through Virgilian and Atokan through Desmoinesian age, respectively.

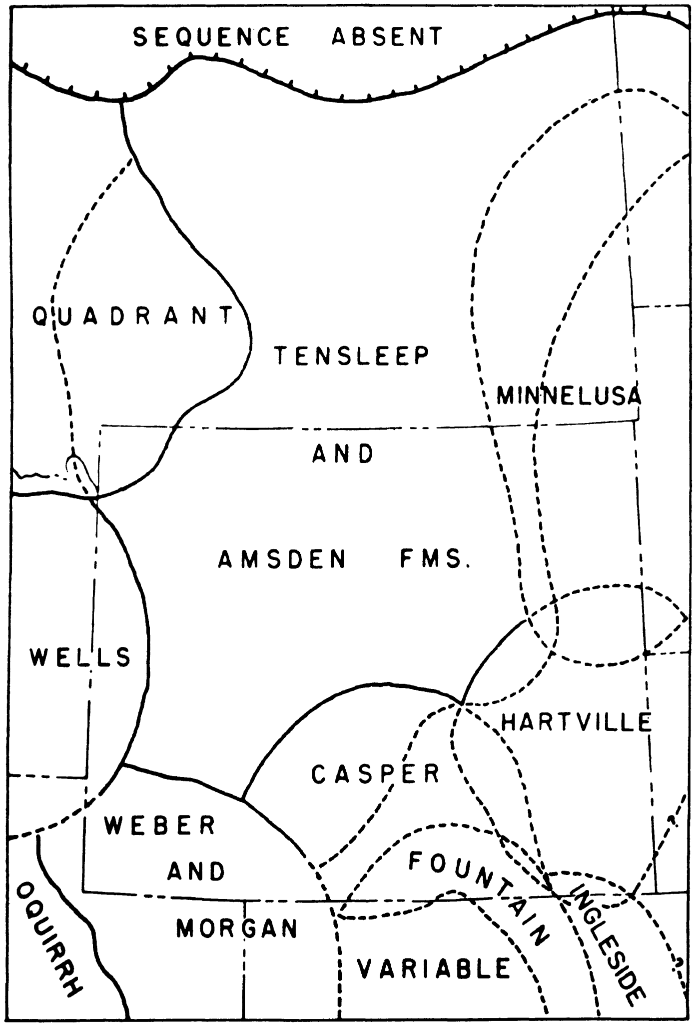

Figure 11A. Permo-Pennsylvanian nomenclature before Wilson (1962). Boundaries are poorly defined, but only the major overlaps in usage are shown by dashed lines

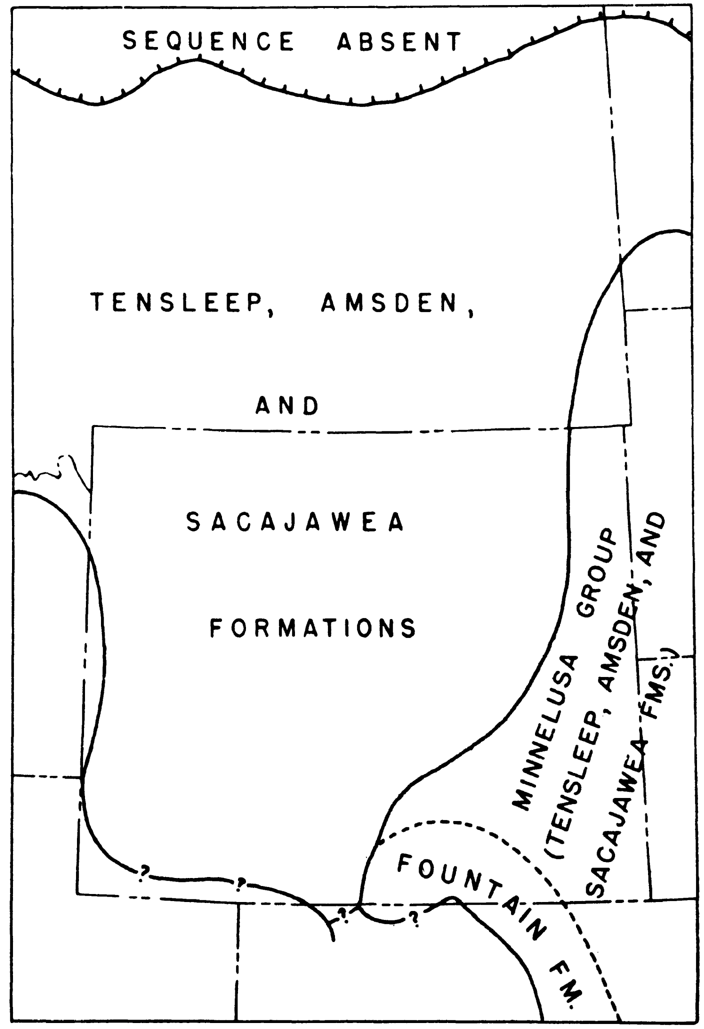

Figure 11B. Nomenclatural areas and terminology recommended by Wilson

Tentatively he designated the terms, "Upper and Lower Hartville" for these generally distinct units. Therefore, Moore assigned the Permo-Pennsylvanian rocks of the Powder River basin to the Minnelusa Group. The upper, predominantly sandstone interval, is the Casper Formation, and the remainder of the section is included in the Hartville Formation (Fig. 12).

The writer is in favor of neither Wilson's (1962) nor Moore's (1970) classification. Lateral and vertical facies changes give rise to great inequalities in degree of subdivision, and this is one reason it is desirable that stratigraphic nomenclature should not be too rigid. The advantage of a rlexible system of local names is that it allows local subdivision to be made as fine as desired without committing oneself to correlation with names from other areas.

It is true the boundary between Wilson's (1962) Sacajawea - Amsden and Moore's (1970) Lower Hartville - Upper Hartville is clear and can be traced from one area to another, but the Amsden-Tensleep and Hartville - Casper boundary is transitional and rarely precise. The thickness of the Sacajawea is affected by the topography of the Pahasapa more than by the conditions of deposition.

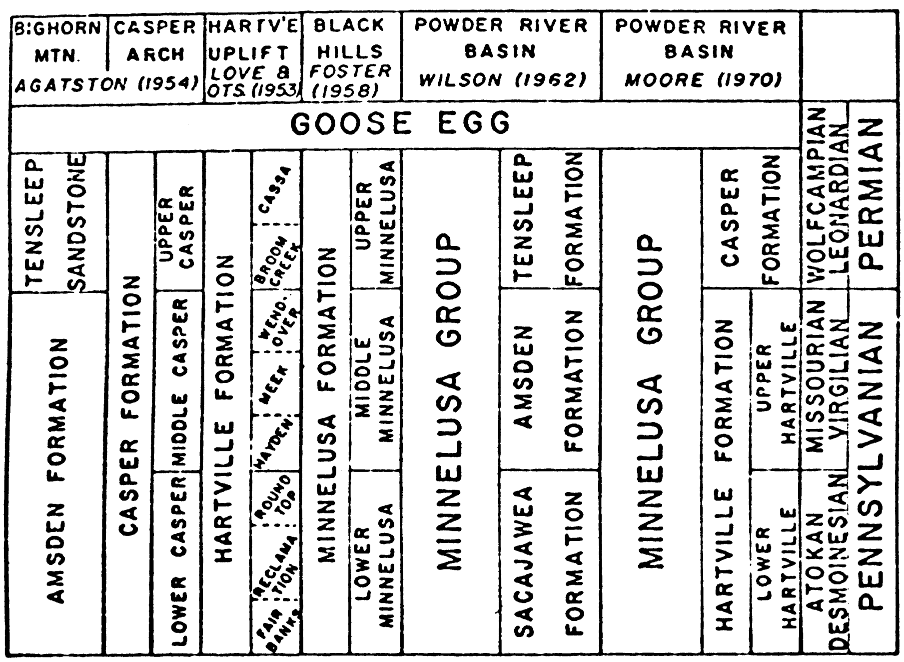

Figure 12. Moore's (1970) nomenclature of Permo-Pennsylvanian sedimentary rocks in the Powder River basin, Wyoming and adjacent areas.

III. FIELD AND LABORATORY PROCEDURES

A. Introduction

The field work was begun during the last two weeks of August 1969. The remainder was accomplished in the summer of 1970. Detailed studies of lithology were made on sections in Boulder Canyon, Spearfish Canyon, Sand Creek and Rapid Canyon. A large number of samples were collected and almost every bed was sampled for hand specimen description and mechanical analysis. Field sampling and laboratory techniques used in this study are given in the rest of this chapter. A total of 156 samples, including 17 composite samples were pre-treated for application of mechanical analysis. But, because it was time-consuming, only 115 samples were sieved. Among these, are the 17 composite samples. The composite samples gave different results and were, therefore, excluded. Size analysis results were used in interpretation of the environment of deposition and description of the sandstones. Amounts of carbonate cement and the silt and clay matrix were also calculated to add more information regarding interpretation of the environment of deposition. The values of the computed parameters and their locations in the stratigraphic sections are shown in the different appendices, so the reader may critically evaluate the author's interpretation or even make his own interpretation if he wishes.

B. Field Sampling

The method of taking a sample differs somewhat according to the purpose of the sampling and the nature of the material as well as the judgement of the collector.

Because the purpose of this study is determining conditions of sedimentation, spot sampling was used. A spot sample is an isolated sample taken at a particular point on the exposure. Such samples are collected separately and kept separately, being thus distinguished from composite samples. Samples were collected from lithologic entities which are believed to make up a sedimentation unit as defined by Otto (1938, p. 575). Precautions were taken not to sample across sedimentation units; but in laminated deposits a number of discrete units (laminae) were included in one sample. Massive sandstones, however, were sampled in as small a thickness as possible to avoid a composite sample representing more than one sedimentation unit. However, a number of composite samples were collected just to see if any difference in results would be obtained. It is absolutely useless to collect composite samples for determining conditions of sedimentation since one is analyzing a mixture of many layers deposited under varying conditions. Almost every bed was sampled including the non-clastic constituents, not all to be analyzed of course, but for hand specimen description and future reference.

In the many cases where much of the material used in the study of the Minnelusa sandstones was well-consolidated, small chips were taken from the most representative part of the bed's exposure. When the materials were of a friable nature, an area on the face of the exposure was cleaned with a hammer and then the fresh face was cut down carefully or scooped out, the rock fragments being caught in a small plastic bag. The principal precaution to be followed is that no weathered or altered phases of the formation be included. This necessitates taking the sample at some distance beneath the surface of the outcrop face.

The size of a sample to be collected in a given case depends mainly upon the coarseness of the sediment and the use to which the sample is to be put. Because the materials were mainly fine sandstones, 300-400 grams were collected, taking into consideration the carbonate cement to be leached, and the amount needed for sieving, and possible thin-sectioning. Wentworth advised not collecting less than about 125 gm. of any sediment regardless of its fineness.

Every sample was numbered or labeled at the time of sampling. A convenient plan, suggested by Wentworth and used by Krumbein and Pettijohn, is to number all samples serially during a given sampling expedition, regardless of their nature or locality. The serial number is made in the field book. Because this author started sampling a section in one area and sometimes changed to another section before finishing the first one, due to transportation arrangements, he used an appropriate number of capital letters to designate the several sections, and the sample of each section was numbered serially, as A-1, A-2,...etc., for one section and B-1, B-2,...etc., for another section. Lower case letter were used to indicate multiple samples taken within a single unit, e.g., A-5a, A-5b, A-5c, etc.

Of equal importance was the care given to the explanation of the position in the rock ledge from which each sample was taken. If a sample was taken from a single foreset layer or from a portion of a ripple layer or mud carck filling or channel filling or any such feature, a brief sketch accompanied the sample so that accurate interpretations can be made from the mechanical analysis. Also, careful field observations were made, and notes taken of minor details and variations. The notes indicated the nature of the bedding, texture, cross-bedding, ripple marks, concretionary zones, gradation of cementation and other prominent lighologic and morphologic features. Such data will increase knowledge of the rock involved, ultimately improving the interpretation made and therefore yielding a true picture of their history.

C. Sample Preparation

A total of 156 samples including 17 composite samples were pretreated for mechanical analysis. The following procedure was used:

1. Disaggregation and Removal of Cement

For the disaggregation of sandstones, the method used depends on the binding material. Procautions to be followed are that the grains should not be broken and that none of the primary constituents should be removed by the disaggregation. According to the nature of the material in this study the following steps were taken:

a. Leaching the Carbonate Cement

All the samples were pre-treated with acid to remove reactive carbonate as there were only very few which do not contain carbonate cement. Before restoring to the acid treatment, however, it was necessary to determine whether any primary calcite fragments were present.

A weighted sample (200-300 gm), was crushed to pea-size chunks or smaller. The fragments were digested in dilute HCl with a concentration of .05 N until effervescence ceased. (It is necessary to be sure the acid is still potent when effervescence ceases). When the sample was dolomite, it was heated gently to hasten solution. The sample was washed carefully with distilled water and oven dried at a temperature of 105-110°C for 8-12 hours. The sample should be well dried because with surface moisture as little as 1-2%, adhesive forces are present, which at grain sizes of less than 1 mm. overcome the weight of the grain (Batel, 1960). When the acid contained any fines, it was poured through filter paper that was previously weighted. The filter paper with the fine material dried at around 60°C and the weight of the finer material was added to the pan fraction.

b. Sandstones with Ferruginous Cement

Ferruginous sands were placed in 50% HCl and warmed over a hot plate. The acid and the ferruginous solution was decanted and the sample was washed and dried as mentioned before.

c. Sandstones Cemented with Silica

For sandstones not strongly cemented with quartz, which was the case with most of the samples, a pounding routine was followed using a rubber cork and mortar. However, when the cement is quartzite and the quartz grains show secondary enlargement, thin-section methods of mechanical analysis are recommended. However no thin sections were made.

d. Sandstones with Clay Matrix

When a clay matrix was present, the sandstone was placed in a wide dish with some distilled water. The sandstone was rubbed with a rubber cork until the clay was in suspension and the grains are separated. The clay was then decanted out and the sand dried as before.

D. Splitting Samples for Analysis

The dried sample was weighed and the percentage of the carbonate cement was calculated. Then the size of the sample was reduced when it was necessary, so that the weight ranged from 80 to 150 grams. A greater quantity makes sieving difficult because the sand clogs the screens. However, numerous screens were used (up to 15) so the sand came to rest on many screens and the size of the sample was not a problem. A smaller quantity would increase the probable error.

E. Mechanical Analysis (Sieving)

1. The split sample was weighed to 0.01 gm., and sieved through two stacks of Tyler eight inch sieves with 1/4 ϕ scale gradations (0.75 phi through 4.0 phi plus pan). The mechanical Tyler Ro-tap sieve shaker was used. Each sample was given a ten minute period of shaking. The length of time was determined by taking three different samples and sieving each one of them for a 10 minute, 15 minute and 20 minute period. After tabulating the various results by percentages, the length of time necessary to stabilize the sieving action was readily apparent, or in other words, a practical "end point" of sieving could be determined. A satisfactory "end point" is considered to have been reached when an additional period of sieving time fails to change the results on any of the sieves used in the analysis by more than 0.5 to 1.0 percent.

2. Each fraction retained on each sieve was weighed to .01 gm. and those amounts smaller than 1.0 gm. were weighed to .001 gm. Such accuracy is necessary when probability paper is used in the plotting because the tails of distribution are so greatly expanded.

3. After being weighed, each fraction was examined with a binocular microscope, and the percentage of aggregates and grains with overgrowth (if any) was deducted from the raw weights as shown in the sample calculation (Table 2).

Table 2. A Sample of the Computation Used for Size Analysis

Field Sample No. B-45
Size of Sample 61.750 gm.

Wentworth Grade Scale MM.	Tyler Screen Opening	ϕ	Weight of Product on Screen	Distributed Error (Screen)	Corrected Weight (Screen)	Percent Aggregates	Corrected Weight	Percent On Screen	Cum Weight	Cum Percent
0.590	0.580	0.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
($\frac{1}{2}$) 0.500	0.495	1.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.420	0.417	1.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.353	0.351	1.50	0.021	0.000	0.021	2.00	0.02	0.04	0.02	0.04
0.297	0.295	1.75	0.182	0.002	0.184	16.00	0.16	0.27	0.18	0.31
($\frac{1}{4}$) 0.250	0.246	2.00	0.309	0.004	0.313	14.00	0.27	0.47	0.45	0.78
0.210	0.208	2.25	2.750	0.037	2.787	10.00	2.51	4.38	2.96	5.16
0.177	0.175	2.50	3.190	0.043	3.233	18.00	2.66	4.63	5.62	9.79
0.149	0.147	2.75	10.100	0.136	10.236	18.00	8.42	14.67	14.03	24.46
($\frac{1}{8}$) 0.125	0.124	3.00	15.450	0.207	15.657	9.00	14.27	24.86	28.30	49.32
0.105	0.104	3.25	11.960	0.161	12.121	2.00	11.88	20.71	40.18	70.03
0.088	0.088	3.50	11.980	0.161	12.141	0.0	12.14	21.16	52.32	91.19
0.074	0.074	3.75	2.420	0.032	2.452	0.0	2.45	4.27	54.78	95.46
($\frac{1}{16}$) 0.062	0.062	4.00	0.350	0.005	0.355	0.0	0.35	0.62	55.13	96.08
PAN			2.220	0.030	2.250	0.0	2.25	3.92	57.38	100.00
		TOTAL	60.932	0.818	61.75		57.38	100.0	57.38	100.0
		LOSS	0.818							

Deduction of aggregates is a critical step that is all too often overlooked in grain size analysis. Failure to do so has a very marked effect on sensitive measures such as skewness and kurtosis, which reflect the normality of the distribution. The Minnelusa sandstone sieve fractions sometimes contained a high percent of aggregates due to the silica cement. When any fraction contained over 25 percent aggregates, it was dissaggregated and run through the screens again.

4. Considerable care was exercised in cleaning the screens after each analysis.

5. The corrected weights were determined and from these, cumulative weights and percentages were derived (by computer). Each cumulative percentage (Table 2, last column from the right) was obtained by dividing each cumulative weight (Table 2, second column from the right) by the total weight. This eliminates errors due to rounding off percentages and also insures that the analysis will end at exactly 100.00 percent, a necessity when using probability graph paper.

6. Data were tabulated and results calculated by computer program.

7. The cumulative percentages were plotted against phi diameter on arithmetic probability paper. It is a waste of time to plot analysis on any other type paper (ordinary squared paper for example) as interpolation between data points is too inaccurate and not reproducible. Values of skewness and kurtosis read off curves drawn on squared paper are worse than meaningless (Folk and Ward 1957).

8. The percentiles 5, 16, 25, 75, 85 and 95 were read off the cumulative curves and the mean size, sorting, skewness and kurtosis were computed for each sample by computer (Appendix B).

IV. DISCUSSION OF RESULTS

A. Computation of the Size Analysis Data

1. Introduction

The size parameters can be obtained from the cumulative curves (graphic measures) or calculated directly from the analysis (moment measures). Graphic measures are superior to moment measures even though the latter can be calculated more rapidly by computer. By not drawing the curve one does not get the "feel" of the data - he does not detect bimodality or "shoulders" in the curves; fails to catch errors caused by faulty screens, etc.; and cannot see genetic relationships that may be brought out by actual inspection of the curves. There is a more serious error in making moment computations: one assumes that the center of gravity of the material within a particular size range is at the center of that class interval. Also, almost all size analyses are open-ended, in that they contain a large proportion of unanalyzed "fines", particularly finer than 4 ϕ (silt and clay). Since the method of moments includes the entire distribution (0 - 100 percentile), if the pan fraction is not analyzed, it is necessary to make some arbitrary assumption about the grain size of the "fines" before a computation can be made, e.g., all material finer than 4 ϕ is arbitrarily considered to be centered at about 10 ϕ. One has the same problem in graphic methods, however, if there is more than 5 percent unanalyzed "fines" using the inclusive measures of Folk and Ward (1957), or more than 16 percent "fines" using the method of Otto (1939) or Inman (1952). Consequently, the "fines" should be analyzed as completely as practicable.

Commonly, the cumulative curves are still drawn using arithmetic percentage ordinates although this practice has been protested strongly by Otto (1939), Inman (1959), Folk and Ward (1957), and many others. All of these workers advocate the use of probability percentage ordinate (graph paper invented by Hazen, 1914; its use for size analysis suggested by Hatch and Choate; 1929) which makes normal distribution curves plot out as straight lines, and is much superior for interpolation. Values of skewness and kurtosis obtained from curves drawn on arithmetic ordinate are utterly worthless because of the uncertainty of interpolating values on an S-shaped curve between data points.

Several graphic measures for average grain size, sorting, skewness, and kurtosis have been proposed in recent decades (Trask, 1932; Otto, 1939; Inman, 1952; Folk and Ward, 1957; McCammon, 1962). A detailed discussion of the graphic measure proposed by these workers is beyond the scope of this study. Today the graphic measures of Folk and Ward (1957) are commonly used. These measures employ the tails and central third of the distribution curve.

2. Statistical Measures Used in the Analysis

a. Mode

The mode is the most frequently occurring grain diameter. Sediments not uncommonly have two or more modes, in which case the most abundant one is spoken of as the primary mode; the others secondary or subordinates modes. There is no simple way or mathematical formula to find the mode accurately. There are many ways it can be approximated. Here, a method suggested by Folk (1968, p. 44) was used.

b. Graphic mean

Inman (1952) used the formula

$$\text{Mean size} = \frac{\phi_{16}+\phi_{84}}{2} ,$$

as a measure of mean size. This serves quite well for normal distribution but is not satisfactory in bimodal and/or skewed distributions. Herein, the following Folk and Ward (1957) formula was used

$$M_z = \frac{\phi_{16}+\phi_{50}+\phi_{84}}{3} .$$

It is the best graphic measure for determining overall size. It corresponds very closely to the mean values as computed by the method of moments, yet is much easier to find. It is much superior to the median because it is based on three points and gives a better overall picture. This will be the standard measure of size used.

c. Graphic Standard Deviation

Graphic standard deviation is a term and value currently used to express an indication of sorting. Inman (1952) followed Krumbein (1938) and Otto (1939) and suggested the phi standard deviation

$$\sigma = \frac{\phi_{84}-\phi_{16}}{2} .$$

It is very close to standard deviation of statisticians but is obtained by reading two values on the cumulative curve instead of by lengthy computation. This sorting measure embraces the central 68 percent of the distribution; thus it is better than Trask's (1930, 1932) sorting coefficient formula. Folk and Ward (1957), feeling that the graphic standard deviation is adequate for normal distribution but inadequate for bimodal or skewed distributions and gives misleading high sorting values, have suggested a new measure called the Inclusive Graphic Standard Deviation, found by the formula:

$$\sigma = \frac{\phi_{84}-\phi_{16}}{4} + \frac{\phi_{95}-\phi_{5}}{6.6} \quad .$$

However, the above observations made by Folk and Ward were not true for the samples studied by this author. For the purpose of comparison of the two values, the writer compared the values from 38 samples (Appendix C) in which the clay and silt content is not more than 5 percent and, therefore the 95 percent percentile is available. The samples include bimodal and trimodal sands but only one sample was unimodal. The values of sorting were calculated by the two different formulas, the Inman (1952) formula and the Folk and Ward (1957) formula. The following results were obtained: The one unimodal sample gave a higher value, by 0.06 ϕ with the Folk and Ward formula; bimodal sands gave from .01 ϕ less to .06 ϕ higher and the trimodal sands from .09 ϕ less to .08 ϕ higher compared to Folk and Ward formula. However, in most of the cases, if not all, these differences did not change the values of sorting from one (verbal) class to another, for example, from very well sorted to well sorted or vice versa. Therefore, the Inman formuma is considered to be satisfactory for this case and was used. Using the Inman formula enabled the writer to calculate the sorting values even for those samples with up to 16 percent unanalyzed silt and clay.

d. Graphic Skewness

Inman (1952) suggested two measures of skewness: one,

$$SK_G = \frac{\phi_{84}+\phi_{16}-2\phi_{50}}{\phi_{84}-\phi_{16}} \quad ,$$

to determine the asymmetry of the central part of the distribution and the other,

$$= \frac{\phi_{95} + \phi_{5} - 2\phi_{50}}{\phi_{84} - \phi_{16}} \quad ,$$

to measure the asymmetry of the extremes.

Folk and Ward (1957), suggested a measure of over-all skewness, obtained by averaging the two Inman formulae values by their Inclusive Graphic skewness formula:

$$SK_1 = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_{5} + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_{5})}$$

Both the Folk and Inman formulae are geometrically independent of sorting.

Again, the author used Inman's formula:

$$SK_G = \frac{\phi_{84} + \phi_{16} - 2\phi_{50}}{\phi_{84} - \phi_{16}} \quad ,$$

for all the analyzed samples and Folk and Ward's (1957) formula for those sample with not more than 5 percent unanalyzed clay and silt (Appendix C). The Result is that there are small differences in the values as in sorting but these differences failed to change the skewness values from one class to another, e.g., positive to symmetrical and vice versa, except in very few cases. Accordingly, the Inman formula was used.

e. Graphic Kurtosis

The graphic kurtosis (K_G) used here is given by the formula (Folk and Ward 1957),

$$K_G = \frac{\phi_{95} - \phi_{5}}{2.44(\phi_{75} - \phi_{25})}$$

This formula gives the ratio between the sorting in the central part of the distribution and in the tails. Because the 95 percentile is used in this formula, the author could calculate the kurtosis only for those samples with not more than 5 percent silt and clay (37 spot samples Appendix C).

B. Frequency Distribution of Size Parameters

For each of the grain size parameters, smoothed frequency curves have been constructed (except for the mode, for which case a histogram was used) to show their range and to serve as a summary of the statistical data.

The values of the sorting, skewness and kurtosis were evaluated according to the verbal scale of Folk and Ward (1957), Table 3.

1. Mode Character of the Sand

The Minnelusa sandstones show up to three modes, 23 percent of the sample are unimodal, and 35 and 42 percent are slighly to strongly bimodal and trimodal, respectively. The primary mode is usually at 3.5 ϕ, but there are quite a few cases where the primary mode is at either 2.25, 2.75, or 3.00 phi; these are usually at the upper portion of the sections where grain size increases. Most of the unimodal sands are from samples representing the lower most sandstone beds in the sections. If the sand modes for all samples are compiled into a histogram distribution (Fig. 13), it is found that the most common diameter is 3.5 phi.

Causes of polymodal distribution are several, among these is faulty sampling, but, because precaution was practiced in sampling and sample preparation, a high level of confidence can be placed on the

Table 3. Folk and Ward Verbal Scale for Sorting Skewness and Kurtosis. All Figures are in Phi-Units. (German Mueller, 1967, Methods in Sedimentary Petrology, Table 11, p. 96.)

Sorting term	Folk & Ward (1957) δ	Fried-man* (1962) δ	Skewness term	Folk & Ward (1957) Sk_I	Kurtosis term	Folk & Ward (1957) K_G
Very well sorted	< 0.35	< 0.35	Very negative skewed	-1.00--0.30	Very platy-kurtic	< 0.67
Well sorted	0.35-0.50	0.35-0.50	Negative skewed	-0.30--0.10	Platy-kurtic	0.67-0.90
Moderately well sorted	0.50-0.70	0.50-0.80	Nearly symmetrical	-0.10-+0.10	Meso-kurtic	0.90-1.11
Moderately sorted	0.70-1.00	0.80-1.40	Positive skewed	+0.10-+0.29	Lepto-kurtic	1.11-1.50
Poorly sorted	1.00-2.00	1.40-2.00	Very positive skewed	+0.30-+1.00	Very lepto-kurtic	1.50-3.00
Very poorly sorted	2.00-4.00	2.00-2.60			Extremely lepto-kurtic	> 3.00
Extremely poorly sorted	> 4.00	> 2.00				

* for sands and sandstones only!

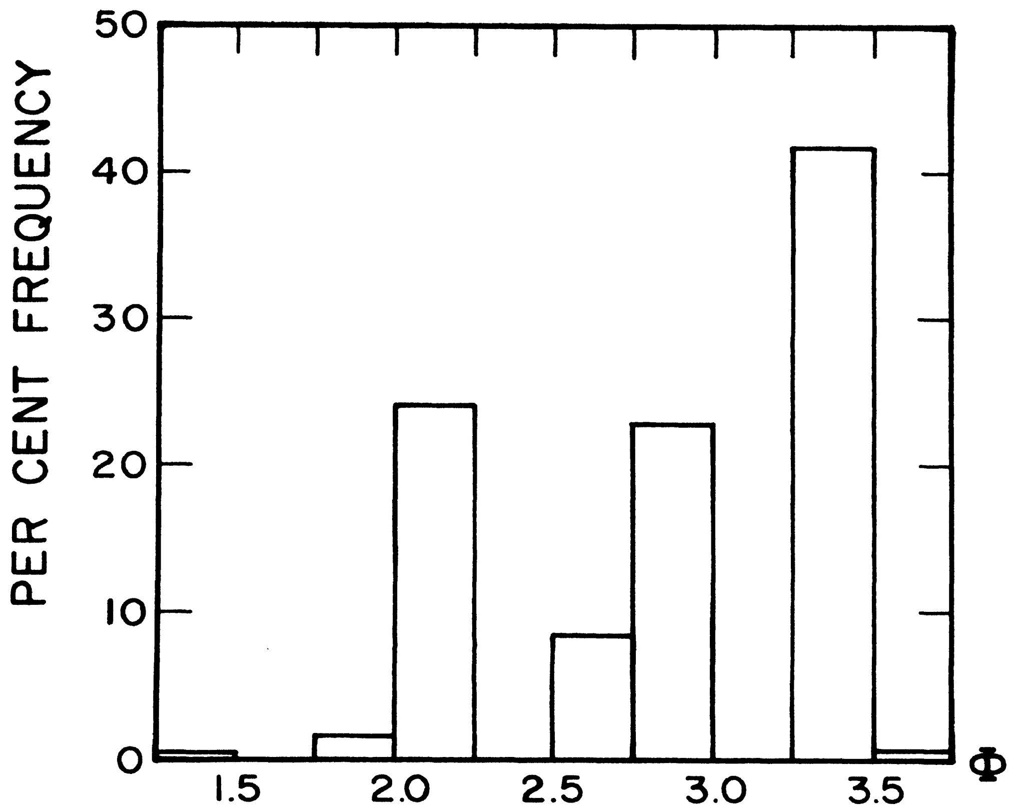

Figure 13. Distribution of the sand modes for all the samples

size analysis results. Therefore, the bimodality must be either due to different sources of supply or the sands reworked from older sandstones that were deposited in different environments. Because the Minnelusa have a similar composition, it is unlikely that the sands came from more than one source area and the bimodality is thus due to reworking of the sand from an older sandstones.

2. Mean Size (M_z)

The distribution of the Folk means are shown in Fig. 14; the extreme values among the 98 spot samples sieved are 2.17 ϕ (.222 mm) and 3.5 ϕ (.088 mm).

The values of M_z for all the sections fluctuate vertically, the variation showing an increase in grain size upward from very fine sand at the base to fine sand at the top. There is no correlation between mean size and sorting.

3. Sorting

Inman standard deviation values range from 0.17 to 0.8 phi units (Fig. 15). The sorting values are variable from sample or group of samples to another. The variation is between very well, well- and moderately well-sorted. The values show no significant trends. Samples from the different sections have about the same range of values.

The distribution of sorting values, according to the textural classification of Folk and Ward (1957), for samples from the various stratigraphic sections are 29 percent very well-sorted, 47 percent well-sorted, 23 percent moderately well-sorted and 1 percent moderately sorted.

Figure 14. Frequency distribution of mean size for 98 samples from all the studied sections. The mean values were grouped in percent of sample per .25 M_z unit.

Figure 15. Frequency distribution of Inman sorting in stratigraphic samples from all the studied sections. The sorting values were grouped into percent of samples per .1 unit.

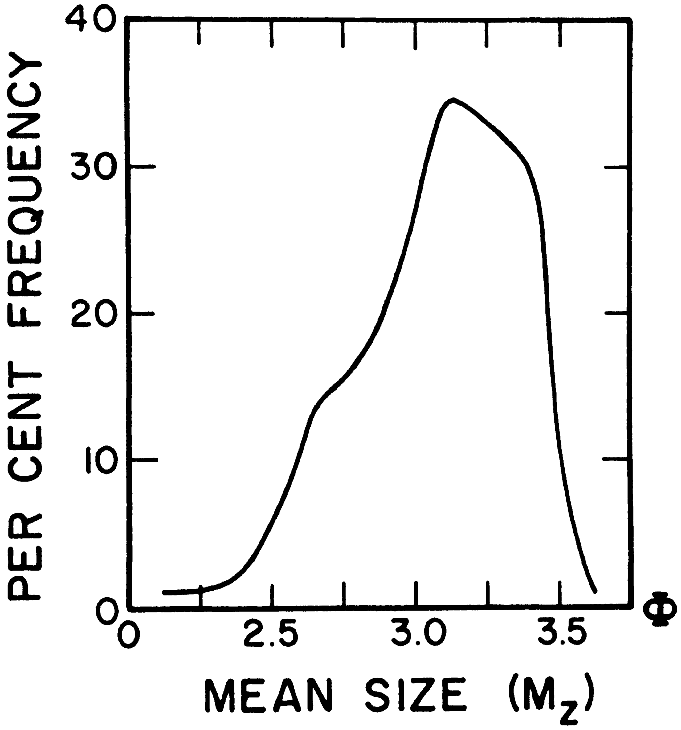

Figure 14

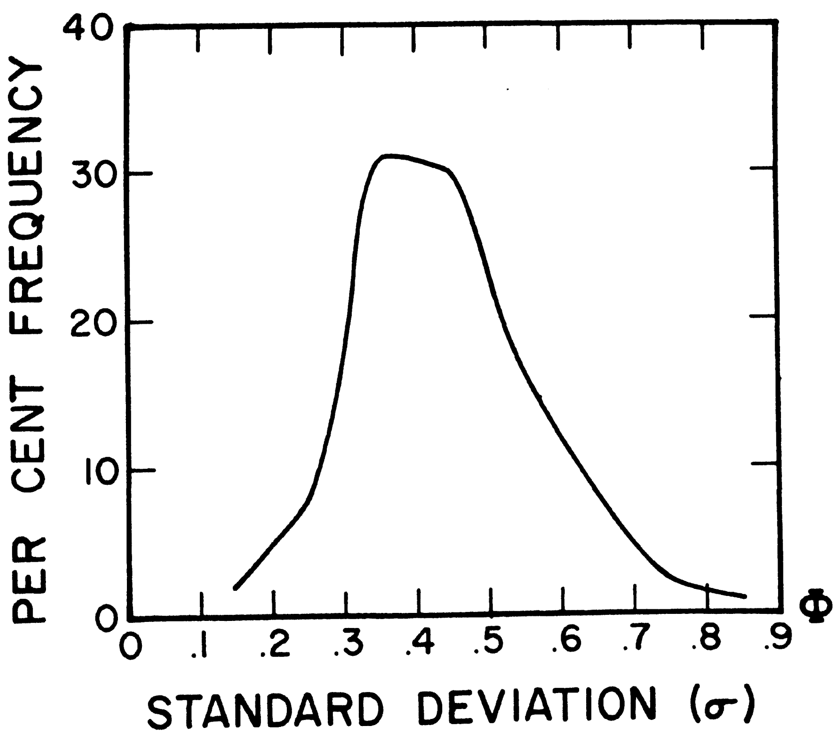

Figure 15

4. Skewness

Inman skewness values ranged widely from very negative (-0.3) to very positive (+.64), but, as shown in Fig. 16, the overall distribution of the values is markedly positively skewed, i.e., it has an excess of fine material. The relatively percentage of skewness types for samples from all the sections are: 5 percent very negative, 22 percent negative, 39 percent symmetrical, 26 percent positive and 8 percent very positive.

5. Kurtosis

Because of the open-endedness of the analyses, the values of kurtosis were not calculated for the samples from all the studied sections. Most of the calculated values are for samples located in the middle and upper portions of the formation. The values of kurtosis range between platykurtic (.75) to leptokurtic (1.41) (Fig. 17). But most of the values are in the mesokurtic and leptokurtic range, meaning that the central portion of the distribution better sorted than the tails. Only 10 percent of the samples have platykurtic values (the tails are better sorted than the center), whereas 44 percent, are leptokurtic and 46 percent are mesokurtic.

C. Carbonate Cement

The carbonate cement was measured by leaching the sample in dilute hydrochloric acid. After leaching, the sample was washed and dried. The difference in weight of the sample before and after leaching was taken as the carbonate cement content. The weight percent distribution of carbonate from samples of the sections are shown graphically in Figure 18; data for individual samples are given in Appendix D.

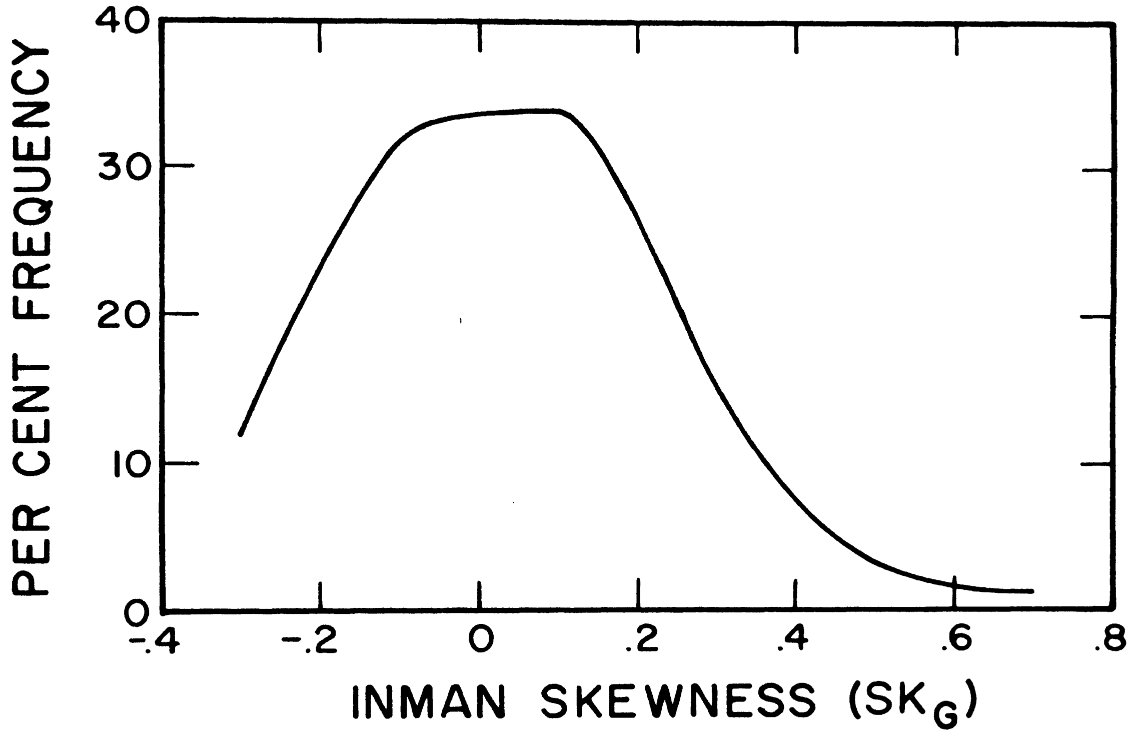

Figure 16. Frequency distribution of Inman skewness values, plotted as percent of samples per .25 K_G

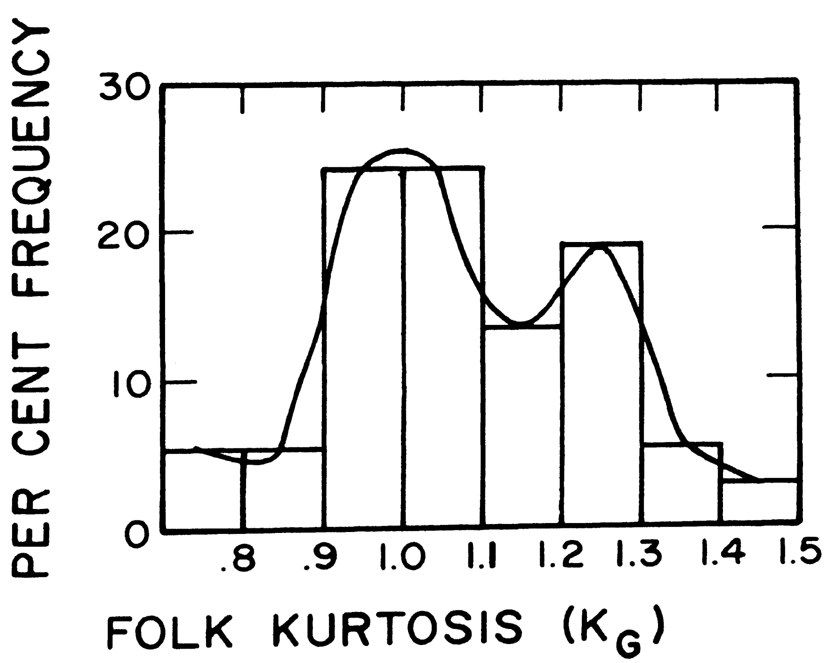

Figure 17. Distribution of Folk kurtosis values plotted as percent of samples per .1 K_G Unit.

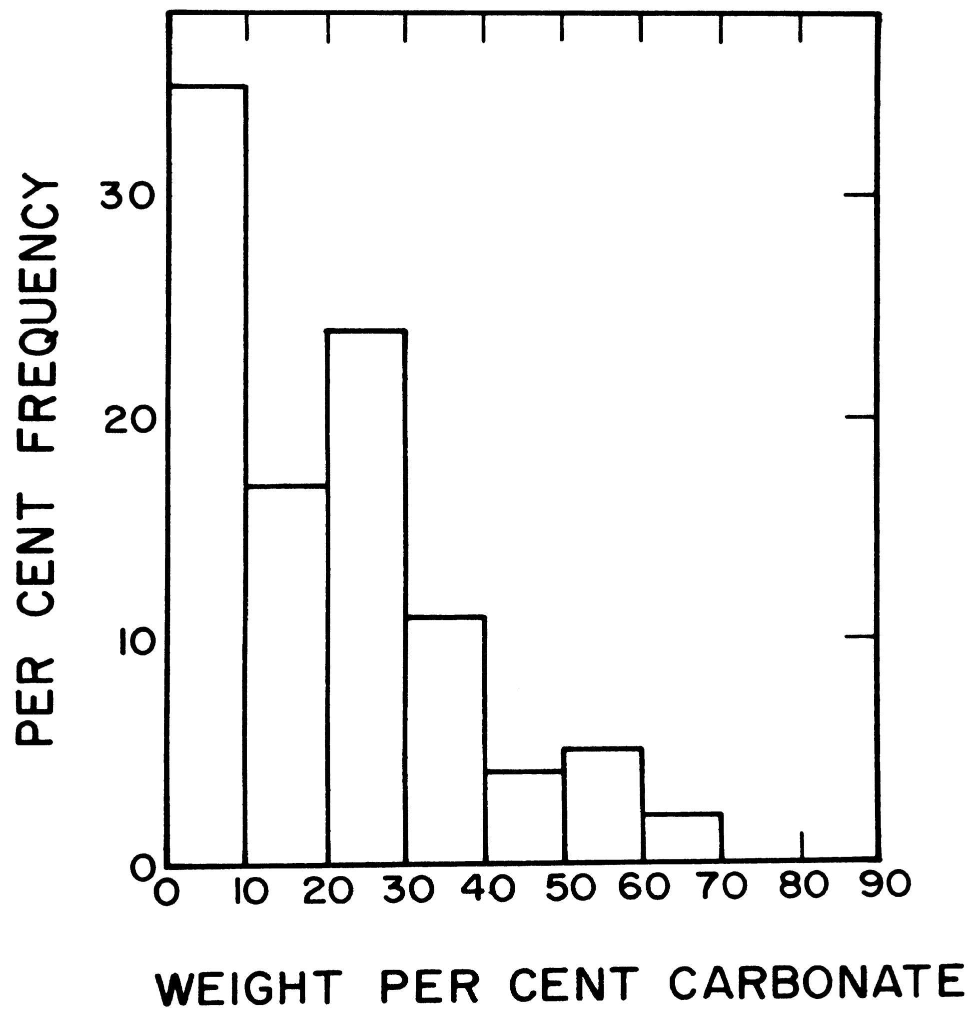

Figure 18. Distribution of carbonate cement in stratigraphic samples from all the studied sections.

Measured values of carbonate cement range between 0 and 68 percent. The distribution of carbonate cement values as a function of mean size (M_z) Figure 19 shows an inverse relationship with grain size, i.e., fine-grained sands contain greater percentages of carbonate. The wide scatter of plotted points may indicate fluctuations in the regime of carbonate deposition.

D. Clay and Silt Matrix

No analyses were carried out for the +4 ϕ sizes, but this pan fraction is considered as a silt and clay. This fraction decreases upward in the stratigraphic section but fluctuations are present also. There is a positive relationship between the carbonate cement and the high silt and clay matrix. The ratio of silt and clay fraction to the sand is given in Appendix D.

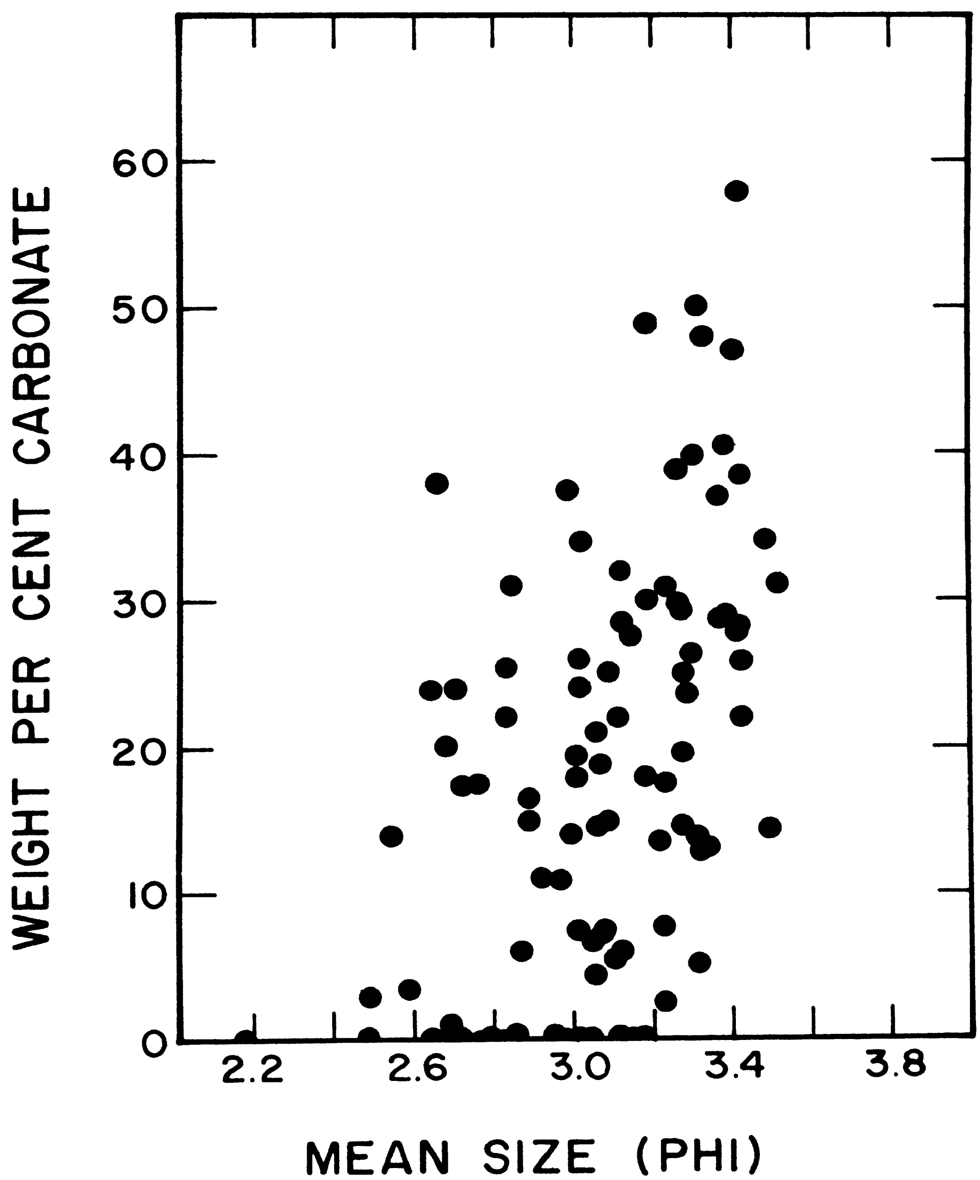

Figure 19. Percent calcium carbonate as a function of grain size for all the sections.

V. ENVIRONMENT OF DEPOSITION

A. Introduction

Knowledge of the environment of deposition sheds considerable light on predicting the geometry of sandstone bodies which is important in connection with oil exploration. The correct identification of depositional environments is requisite to any successful search for stratigraphic traps and the potential distribution of reservoir sands.

Since 1900, many attempts have been made to develop a genetic interpretation of sediments based on a study of textures of clastics.

Udden (1898, 1914), Wentworth (1922, 1929) Trask (1932), Krumbein and Pettijohn (1938), Otto (1939) and others have applied various statistical coefficients to characterize the size frequency distribution of clastic sediments. Recently, Folk and Ward (1957), Mason and Folk (1958), Harrison (1959) and even more recently, Friedman (1961, 1962, 1967), Fuller (1962) and others have attempted to use the statistical measures of mean, standard deviation, skewness, and kurtosis to separate beach, dune, and fluvial environments of recent sands. These attempts have met with moderate success with recent sands, but have been generally unsuccessful in interpreting the environments of deposition of ancient sediments. Passega (1957; 1964) developed so-called C/M plots with which by using a number of samples, it is possible to distinguish suspension, traction, graded suspension, and other sedimentary processes. Unfortunately each of these transportation mechanisms occurs in many environments.

A new criterion for the recognition of depositional environments which is used in this study, has been developed during the past decade. It has been recognized that no single approach can uniquely define environments of deposition, but a combination of variables such as mineral composition, vertical grain size changes, sedimentary structures, and morphology of the sand body as well as the biologic aspects needs to be considered. These data, excepting morphology and the biologic aspects, are particularly useful if considered in a vertical succession. These parameters have been used with a considerable success in diverse environments by Visher (1965), Potter (1967) and others.

Mineral composition has been successfully used in delineating environments of deposition. For example, the presence of large quantities of clay matrix generally indicates a low energy environment such as a lagoon, while highly quartzose sandstones are generally marine in origin. However, differences in composition of sediments may also reflect a wide range of composition in the source rocks.

The relative abundance of rock fragments has been used as an indication of fluvio-deltaic rather than near-shore marine environments within the same basin of deposition (Berg and Davis, 1971).

Carbonate cement increases upward in a regressive marine environment and down in a transgressive one. This is due to the relation between grain size and percent cement. In this regard Moore (1970, p. 133) stated that:

> "...with decreasing size, grains generally become more angular and are thus able to achieve a closer packing density than large grains, thus reducing pore space. With increasing grain size, pore size increases and thus cement increases. For similar reasons, this positive relation holds for grain size and sorting..."

Most of the Minnelusa sandstones are quartzose and polycyclic with little matrix and no rock fragments; this would indicate deposition in relatively shallow water and a high energy environment. There are certain units which contain a relatively high ratio silt and clay matrix which reflect lagoonal and/or offshore sediments.

Carbonate cement values in the Minnelusa generally show an inverse relationship with grain size (Fig. 19, p. 55), i.e., the amount of carbonate cement increases with a grain size decrease. This is opposite of what would be expected if the carbonate originated secondarily be concentration from migrating groundwater. If this were the case, the pore space and the permeability would effect the concentration of the carbonate cement. Therefore, the carbonate cement is interpreted here in terms of primary carbonate deposition.

Grain size parameters have also been used to determine environments. Marine sands tend to be finer and better sorted than fluvial sands...etc. Folk and Ward (1957), Mason and Folk (1958), Friedman (1962; 1967) and others, report that beach sands are positively skewed and dune and river sands negatively skewed, but a number of exceptions are reported. The values of skewness are relatively dependent on the rate of supply and energy available. Minnelusa sandstones are fine- and very fine-grained (.222 to .088 mm.), and sorting ranges from moderately well-to very well-sorted (0.17 to 0.8 ϕ) sandstones indicating high energy environments. Values of kurtosis show that differences in samples exist almost entirely in the "center" of the curves which indicate that the skewness and kurtosis in this study are not sensitive to environment of deposition. Also, most of these sandstones are bimodal or polymodal, so that such additional modes, in fact, become more important in influencing the sign of skewness than the presence or absence of fine-grained or coarse-grained tails.

Studies of recent sands and ancient sediments indicate that in some cases the values of grain size parameters, within a vertical profile, exhibit systematic variations and the determination of this variation and magnitude of change is important. For example, grain size within a regressive marine will increase upward whereas in a transgressive one, grain size decreases upward (Berg and Davis 1971). Grain size is also enlarged by secondary overgrowths. Though this diagenetic effect occurs, its influence on grain size analysis was isolated as indicated earlier. The Minnelusa sandstones are in the very fine and fine sand-size range, increasing upward, indicating a regressive marine environment of deposition. All sections show two cycles of increasing grain size upward except the Boulder Canyon section which shows an increase upward without remarkable fluctuations.

Primary sedimentary structures provide information on the manner in which the depositional medium applies energy to clastic detritus. Cross-bedding, graded bedding, ripple marks...etc. characterize both the process of sedimentation and a specific depositional environment. Most sedimentary structures are not uniquely restricted to a single environment, but where a combination of structures suggests a specific environment of deposition they may be used with some confidence. In this study, the primary structures were studied in qualitative terms only. These include cross-bedding sets which are mostly wedge-shaped (Fig. 10A, B, p. 22) and ripple marks which are scarce and not well preserved but are quite common in the middle beds, indicating shallower water conditions.

Morphology is important as an environment indicator. Barrier bars tend to be elongated bodies parallel to depositional strikes whereas fluvial deposits are often curvate and trend perpendicular to the strand line. Compaction of clay and sand changes the original shape. However, in the Minnelusa, because the sandstone is interbedded with carbonates, the sands probably reflect more closely their original shape, because carbonates, especially carbonate muds, compact only a little. The lower Minnelusa and the lower part of the middle Minnelusa is thick-bedded sandstone, the thickness decreasing upward, indicating a transgressive marine cycle. The middle of the formation is medium to massive bedded, ledge-forming. Each younger bed in the vertical sequence indicates deposition slightly seaward from the underlying one. The upper Minnelusa consists of massive, cliff-forming sandstones. Within these, grain size increases upward sometimes as a single uniform pattern (as at Boulder Canyon, unit 1) or more than one cycle of decreasing sand size (Spearfish Canyon, unit 1 through 5). These are interpreted as having formed in a regressive sea.

Biological aspects are informative with regard to depth of water, turbulence, salinity, water temperature, the rate of sedimentation, and the nature of the depositional interface. Collectively these parameters define a depositional environment (Visher, 1965). Literature indicates that fusulinds are relatively common in the southern Black Hills, but rare to the north in the area of study. The fossils of northern portion of the Black Hills are largely molluscs and brachiopods, indicating a transition to a near-shore environment.

B. Depositional Environments of the Minnelusa

The specific environment of deposition of the Minnelusa Formation is difficult to ascertain due to many variations in its lithology. On the basis of vertical grain size changes, composition, primary structures, morphology, thickness in bedding, and fossils the following environments are suggested:

The Minnelusa of the northern Black Hills uplift was deposited in a near shore, shallow water sea. The lower beds and possibly the lower part of the middle of the formation were deposited in a transgressive sea. The rest of the formation was deposited during regressive and transgressive cycles due to the variation in rate of subsidence of the area. When the submergence continued at a rate slightly slower than sedimentation the filling-in process was continued until the upper portion was exposed with formation of the beach ridges of the middle beds of the middle Minnelusa. The very fine-grained and silty red bed at the top of the middle of the formation in the Rapid Canyon section to the south may have been deposited in a lagoon associated with the beach. Also the brecciated silty sandstone of the lower part of the upper Minnelusa at Rapid Canyon and Sand Creek could have been deposited in a lagoon or near-lagoon environment, assuming, however, that this brecciation was caused by removal of evaporites as proposed by Bates (1955). The remainder of upper Minnelusa is a regressive near-shore marine. When the submergence was at a more rapid rate, the sequence was completed by the transgression of the sea. This explains quite well the variations of lithology particularly the marine carbonates and shales. The author believes the deposition of the Phosphoria marine carbonates on the Minnelusa on the western flank of the Black

Hills and continental shale of the Opeche Formation on the Minnelusa on the eastern flank represents a facies relationship. No erosion surface was observed at the base of the phosphoria and subsidence difference in the lithologies. The source of Minnelusa sediments is probably deltaic.

The solution zone at the base of the formation represents either a reqorked residual mantle derived from Mississippian limestone or anhydrite solution.

C. Source Area (Provenance)

In this study no regional work was done, but a review of the literature suggests that the source of sediments lay to the north and northeast, but cannot be specifically identified. Evidences of this are the outcrops of the sequence and thinning to the north and northeast with increasing sandstone and loss of carbonates and shales (marine) are expected to increase offshore at least for a short distance. Fossils are common to the south, but rare or absent to the north of the Black Hills; the fossils of the northern portion are largely molluscs and brachiopods, indicating perhaps transition of near-shore environment. Direction of cross-bedding and ripple marks indicate that, during Minnelusa time, sediments entered the area from northeast and were dispersed uniformly in a west and southwest direction.

Wilson (1962) constructed an isopach-lithofacies map of the Minnelusa in Powder River basin and adjacent areas. He interpreted a southwesterly source, but for reasons mentioned above this is unlikely at least for the Black Hills uplift.

The sand grains studied here are of two distinctive types. A very small portion of larger grains are very well rounded and of extremely high sphericity. These quartz grains probably inherited from other sands. The other sand is subrounded translucent. In addition, the relative mature character of the sand might indicate the Minnelusa sands were derived of older sedimentary rocks.

VI. Summary

The Minnelusa Formation in the northeastern and northwestern Black Hills uplift is divided into upper, middle and lower parts. The upper portion of the sequence is quartzose sandstone with little limestone and shale, calcareous to non-calcareous, and locally is selectively silica-cemented. It is massive, forming cliffs, cross-bedded with dips trending southwest. The sandstone is yellow, buff, and gray, fine-grained. The middle portion is composed of sandstone with carbonate members and shale. The sandstone is gray, white, pink, and red near the top of this portion of the formation. It contains varying amounts of calcareous and dolomite cements and overgrowths. The beds are variable in thickness and are ledge-forming have lumpy weathered surfaces; cross-bedding is common and is wedge-shaped and dips southwest. The contact between the upper and middle beds is gradational and not definite. The lower beds at the base are a persistent unit made up of pink, very dolomitic, micaceous sandstone and siltstone and arenaceous dolomite and red shale; interbedded with it are hard thin dolomite beds. At the base of the formation is a solution zone often represented by contorted beds.

The statistical data are based on a series of grain size parameters of Inman (1952) and their modifications by Folk and Ward (1957). Unimodal sediments and polymodal sediments were identified by their number of modes. The mean size (M_z) ranges from very fine to fine and shows trends which can be applicable in the interpretation of the environment of deposition. Sorting, skewness and kurtosis are variable and do not show any trends or correlation with mean size (M_z). The sands, as defined by their kurtosis, are better sorted in the center of the distribution than the tails. In addition the sand is polymodal; therefore, neither skewness nor kurtosis are sensitive enough to be diagnostic and they were not used in interpretation of the environment of deposition. Carbonate cement shows an inverse relationship with grain size indicating that the cement is primary in origin. The silt and clay matrix decreases upward with some fluctuations.

The environment of deposition was delineated mainly by vertical changes of grain size and partly by sorting, composition, primary structures, variations in thickness of the beds, morphology and fossils. The sand was deposited in a regressive series in an environment which included offshore bars, lagoons and beaches. This regressive sequence is present in all sections. It is possibly caused by subsidence of the area and variation in the rate of deposition. The source is deltaic.

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VITA

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He is a member of the American Association of Petroleum Geologists, the Society of Economic Paleontologists and Mineralogists, the American Society of Photogrammetry and the American Association for the Advancement of Science.

Mr. Taleb is presently employed as a geologist by Esso Standard Libya, Inc.

APPENDICES

A. Description of Measured Stratigraphic Sections

Following are sections of the Minnelusa Formation measured at good exposures in the northern and northwestern Black Hills. Each description includes: 1) graphic representation of the section showing all the units involved, numbered from youngest to oldest, and the location of the analyzed samples, 2) scale for all sections is one inch equal 20 feet and 3) a written description. The thicknesses are given in feet and tenths of feet.

Explanation of the symbols and numbers used in the description of the stratigraphic sections are given on the next page (Fig. 20).

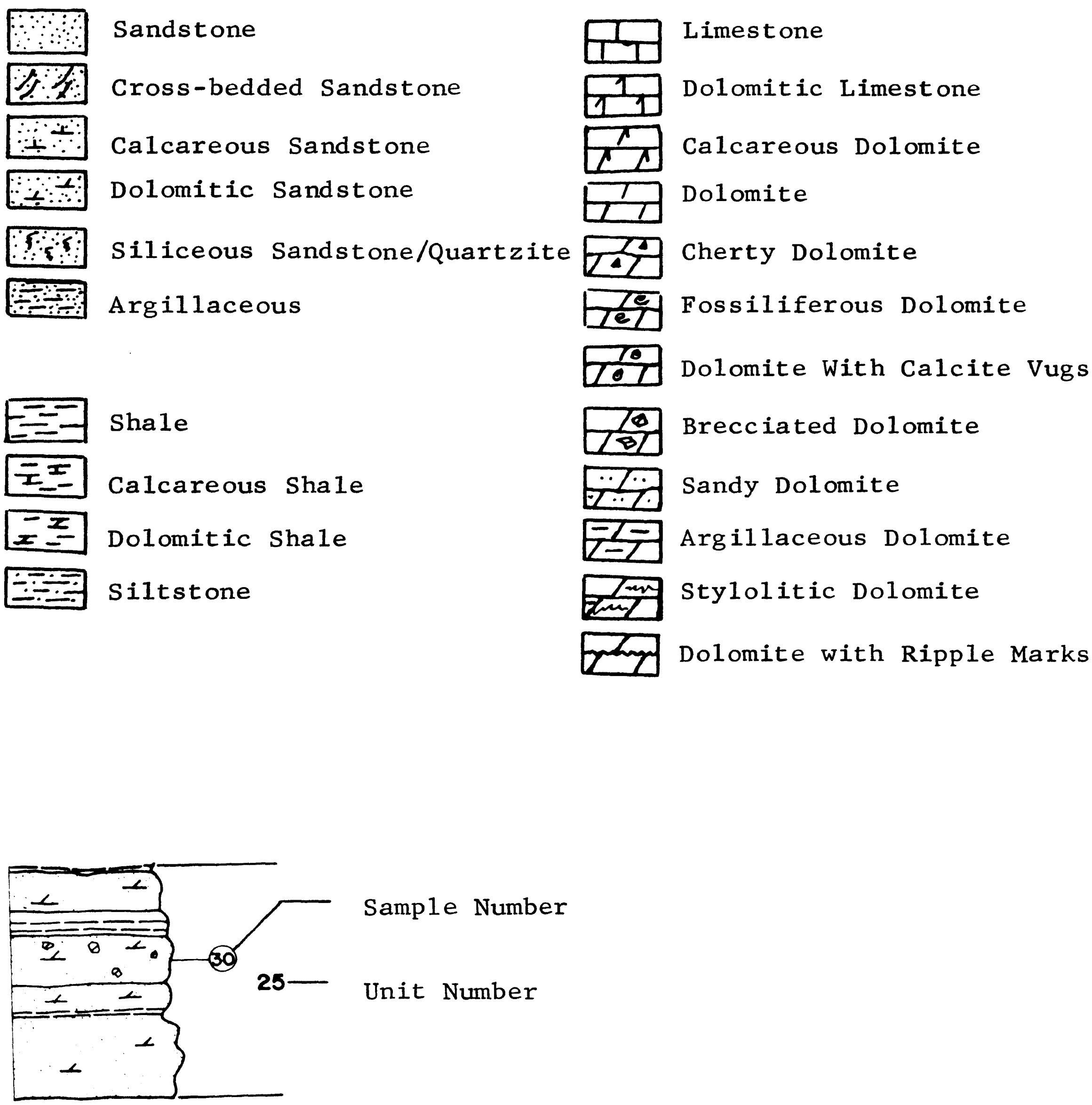

Figure 20. Explanation of symbols used on stratigraphic sections, Figures 21 to 25.

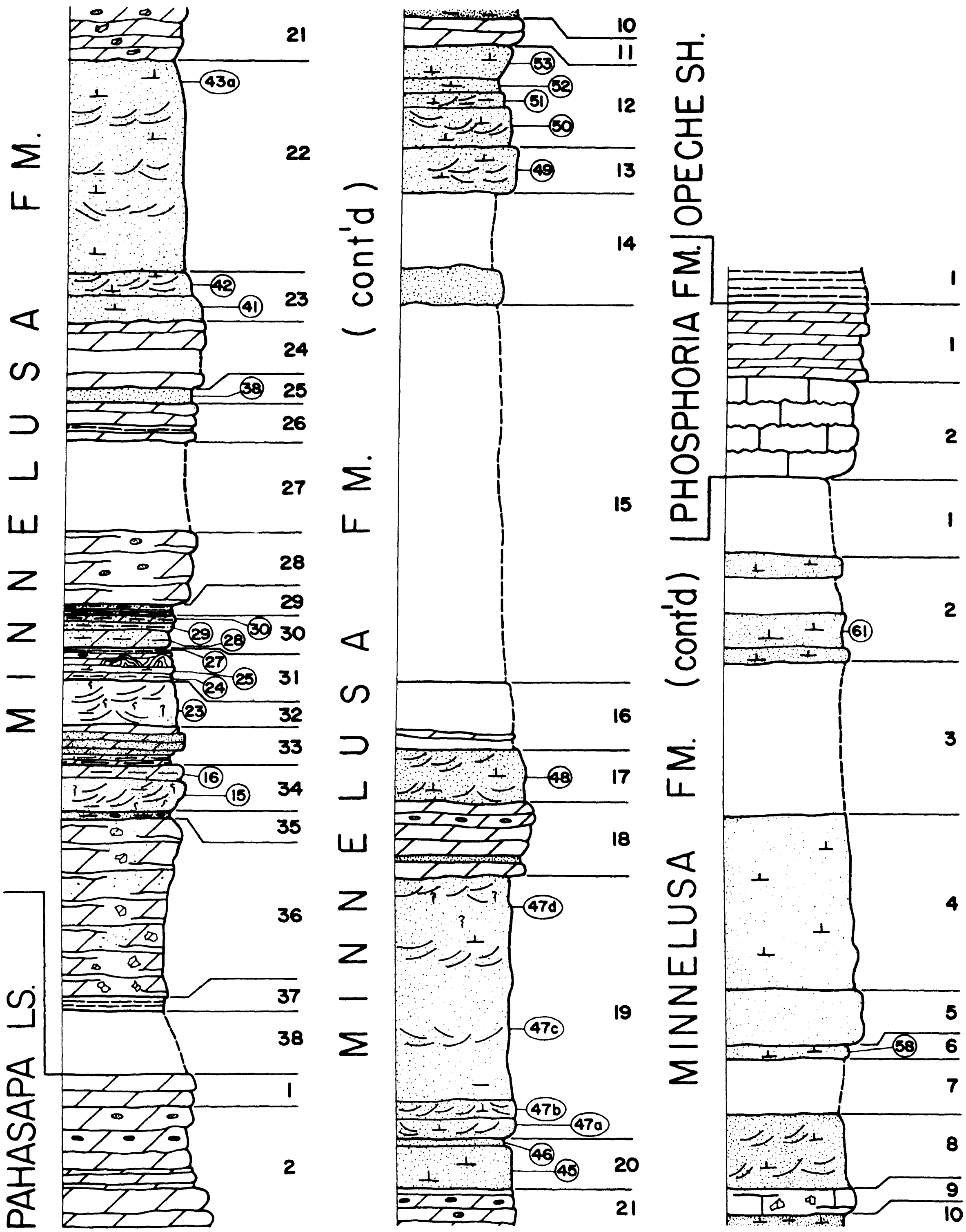

Figure 21. Sand Creek Section

1. SAND CREEK SECTION

Measured in Sand Creek Canyon, Sec. 13, T. 52N., R. 61W., Crook Co., Wyoming. Section is at Ranch A, near U.S.D.A. fish laboratory. Measured with rule and hand level.

Unit No.	Description	Thickness in feet
	Opeche Formation (Permian)	
	Shale, red, sandy and sandstone, red; mostly covered...	Not measured
	Phosphoria Formation (Permian)	
1.	Dolomite, pink, fine-grained, medium- to thick-bedded, with calcite-lines cavities	9.5
2.	Limestone, dark gray, coarse-grained, granular, contains ripple marks	13.3
	Total thickness of Phosphoria Fm	22.8
	Minnelusa Formation (Permo-Pennsylvanian)	
1.	Covered	10.0
2.	Sandstone, calcareous, buff, fine-grained, friable, thick- to massive-bedded, partly covered. Two feet at base gray, very calcareous, hard	11.6
3.	Sandstone, not well-exposed, laterally brecciated	20.0
4.	Sandstone, calcareous, white to gray, massive, collapsed, cliff forming, laterally brecciated	24.0
5.	Sandstone, calcareous, gray, very fine-grained, massive, very hard but soft near top	5.0
6.	Sandstone, calcareous, yellowish brown, fine-grained, hard	1.7
7.	Covered	7.00
8.	Sandstone, calcareous, yellowish brown, fine-grained cross-bedded with SW dips; massive, hard, soft at top	9.5
9.	Limestone, gray to pink; has fracture-filling pattern; brecciated, massive	3.5

10. Sandstone, calcareous, argillaceous, red..................2.0

11. Dolomite, pink to gray, with calcite streaks parallel to the bedding planes............................4.0

12. Sandstone, yellow, calcareous, yellowish brown-speckled with limonite stains, fine-grained, massive, cross-bedded with NW dips, very distinctive knobby surface..........................13.3

13. Sandstone, as above, but very fine grained................6.0

14. Sandstone, red, mostly covered............................15.0

15. Covered...49.5

16. Dolomite, thin- to medium-bedded, covered, outcrops at base of talus above.............................9.50

17. Sandstone, red, fine-grained, cross-bedded with ripple marks and box-work, partly covered.................7.0

18. Limestone, light gray, fossiliferous (gastropods and unidentified molds), with one bed of sandstone near base...8.0

19. Sandstone, slightly calcareous, siliceous, buff to pink, calcareous, fine-grained, friable, cross-bedded with SW dips, massive, cliff-forming...............34.1

20. Sandstone, calcareous, grayish orange, very fine-grained, massive, friable, knobby-weathering; grains larger than 0.5 mm are mainly chert; hard but 1.4 feet at top is soft..............................7.4

21. Dolomite, calcite, gray, dense, brecciated, vuggy; chert nodules at top..............................10.5

22. Sandstone, calcareous, purple to gray, very fine-grained, friable, one massive unit, weathers to knobby surface...25.0

23. Sandstone, calcareous, purple to gray, very fine-grained thick-bedded, moderately hard; lower part argillaceous; cross-bedded at top........................6.3

24. Dolomite, light gray, fine-grained, thick- to massive-bedded, partly covered............................8.4

25. Sandstone, slightly calcareous, pinkish gray, very fine-grained, friable..............................2.0

26. Dolomite, light gray, thick-bedded, interbedded with lenticular gray shale....................................5.7

27. Covered..12.0

28. Dolomite, gray, thick to massive-bedded, (2-4 feet) vuggy, hard, ledge-forming........................9.6

29. Dolomite, sandy, argillaceous, gray, very fine-grained, interbedded with lenticular gray shale..............1.5

30. Sandstone, dolomitic, arenaceous dolomite and dolomitic claystone, micaceous, pink to gray with irregular lamination.......................................4.2

31. Sandstone, dolomitic and arenaceous, silty dolomite, pink, very fine-grained; possible algal laminations; gray soft shale at top.................................... 4.1

32. Sandstone, very dolomitic, siliceous, silty, very fine-grained with iron oxide streaks, very hard, massive.. 6.1

33. Dolomite, arenaceous, micaceous, grayish pink, medium- to thick-bedded with irregular laminations of claystone. One bed of hard dolomite at top.............. 4.9

34. Sandstone, dolomitic, siliceous, bands of various colors, very fine-grained, laminated, brown-spotted (due to iron oxide). Silty, arenaceous, pink dolomite with molds of fossils at top...................... 6.5

35. Sandstone, dolomitic, purple-red, very fine-grained, cherty.. 1.0

36. Dolomite, sandy, gray, vuggy, brecciated, contorted; contains chert nodules.................................23.0

37. Shale, calcareous, gray to purple, soft.................... 2.0

38. Covered slope... 8.0

Total thickness of Minnelusa Formation...............398

Pahasapa Limestone (Mississippian)

1. Dolomite, calcitic, sandy, light gray, coarsely crystalline, thick-bedded, ledge-forming................... 4.7

2. Dolomite, calcitic, light pink to medium light gray, coarse-grained, composed of rhombs of dolomite; contains chert nodules and vugs filled with calcite; medium- to thick-bedded, uneven bedding............11.0

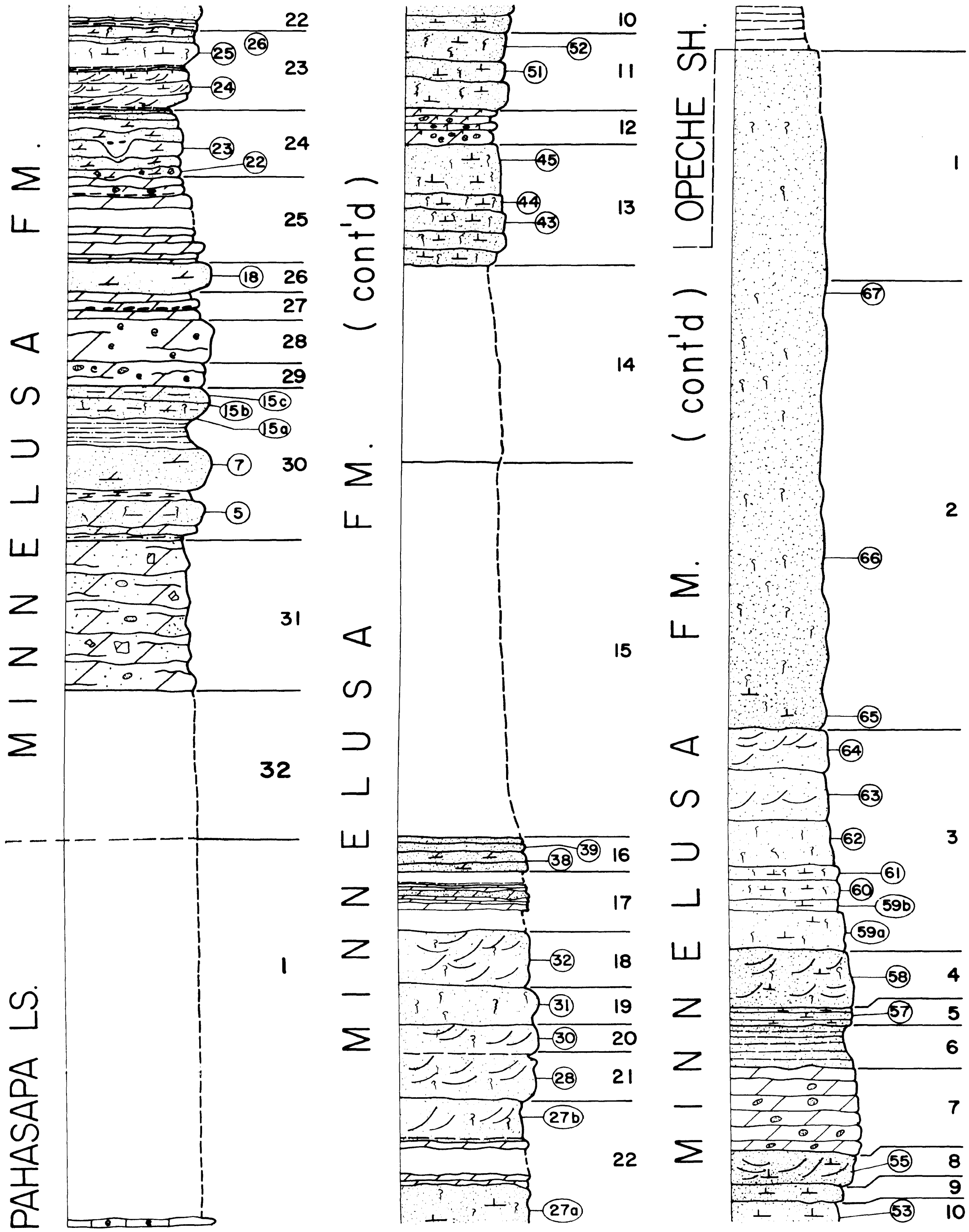

Figure 22. Spearfish Canyon Section

2. SPEARFISH CANYON SECTION

Measured in Spearfish Creek Canyon, Sec. 27, T.G.N., R. 2E, Lawrence Co., S. Dakota. Section is 1 1/4 miles south of Spearfish. Measured by rule and hand level.

Unit No.	Description	Thickness in feet
	Opeche Formation (Permian)	
	Shale red, sandy and sandstone, red, mostly covered	Not measured
	Minnelusa Formation (Permo-Pennsylvanian)	
1.	Sandstone, siliceous, not well-exposed; contact is covered	30.0
2.	Sandstone, siliceous, buff to yellowish brown, fine-grained, cliff-forming	60.0
3.	Sandstone, siliceous, calcareous, buff, fine- to very fine-grained, thick- to massive-bedded; upper part cross-bedded with dips to the south; lower part laminated; bedding planes not continuous	29.1
4.	Sandstone, siliceous, calcareous, pink to yellowish brown, massive, cross-bedded	7.6
5.	Sandstone, calcareous, medium-bedded with scattered patches of white calcite	2.7
6.	sandstone, slightly calcareous, argillaceous, soft	5.7
7.	Dolomite, calcareous, buff, fine-grained, medium-bedded, weathers soft. Contains vugs filled with calcite; fossiliferous (productid brachiopods)	10.8
8.	Sandstone, calcareous, yellowish brown, very fine-grained, massive, siliceous, cross-bedded with SW dips	4.0
9.	Sandstone, calcareous, siliceous, pink, very fine-grained, thick-bedded, laminated	2.3
10.	Sandstone, calcareous, yellowish brown, fine-grained, massive, siliceous, very hard	6.0

11. Sandstone, siliceous, calcareous, very fine-grained, lower part with fracture-filling patterns, thick-bedded....................................10.1

12. Dolomite, pink, fine-grained, medium- to thick-bedded, soft, vuggy; has fossil molds at bottom (brachipods, spines and possible trilobites); brecciated at top; contains ripple marks with N-S trend..4.9

13. Sandstone, siliceous, calcareous, pink to creamy white, very fine-grained, no distinctive beds, very hard...16.0

14. Talus..26.0

15. Covered slope, soil......................................55.0

16. Sandstone, non-calcareous, pink, fine-grained, medium- to thick-bedded, friable, stained yellowish brown due to iron oxides..............................4.7

17. Dolomite and arenaceous, silty dolomite; gray, fine-grained, thin- to medium-bedded; purple at top; contains molds of fossils...........................7.4

18. Sandstone, very slightly calcareous to non-calcareous, siliceous, fine-grained, creamy white, massive, friable, cross-bedded, ripple marks with NNE-SSW crestal trend.....7.1

19. Sandstone, non-calcareous, siliceous, pink, fine-grained, massive, friable, stained yellowish brown due to iron oxides.......................................5.4

20. Sandstone, non-calcareous, siliceous, white, very fine-grained, massive, friable, cross-bedded with SW dips, and gray, fissile shale at bottom................3.9

21. Sandstone as above but fine-grained......................5.8

22. Sandstone, calcareous, siliceous, moderately orange-pink, very fine-grained, massive, weathers to knobs; interbedded with thin shale and dolomite beds; upper part cross-bedded with dips to south, lower part with indefinite ripple marks........................25.3

23. Sandstone, calcareous, siliceous, purple at bottom and gray at top, very fine-grained, medium- to thick- and wavy-bedded; well-indurated; weathers to knobs; lower part cross-bedded with SW dips. Interbedded with shale...11.0

24. Sandstone, dolomitic, pink, very fine-grained, thin- to thick- and wavy-bedded; brecciated at bottom with channel filled with limestone and chert fragments..8.7

25. Dolomite, light gray with maroon streaks, wavy-bedded at top; orange-pink, calcareous, thick-bedded, partly covered in the middle; purple; thin- to medium-bedded, hard at bottom............11.2

26. Sandstone, dolomitic, reddish, very fine-grained, massive, ledge-forming, hard. In some places ripple marks have N-S trend.......................4.0

27. Dolomite, argillaceous, purple to gray, fine-grained, with chert layers and calcite geodes; medium- to thick-bedded..................................3.6

28. Dolomite, light to medium gray; fossiliferous (pelcypods, crinoid columnals, brachiopods and bryozoans); massive.......................................5.2

29. Dolomite, gray to pink, with molds and vugs lined with calcite crystals; massive, moderately hard...........3.3

30. Sandstone, siliceous, pink, very fine-grained; grades up to arenaceous dolomite. Interbedded with shale and siltstone; thick- to massive-bedded; eroded into ledges...20.6

31. Dolomite, sandy and calcareous, coarse-grained, composed of dolomite rhombs; cherty, massive, brecciated, highly affected by solution activity..........15.0

32. Covered slope to Pahasapa Limestone......................20.0

Total thickness of Minnelusa......................426

Pahasapa Limestone (Mississippian)

1. Covered, fossiliferous limestone bed 50 feet below arbitrary contact.......................................50.0

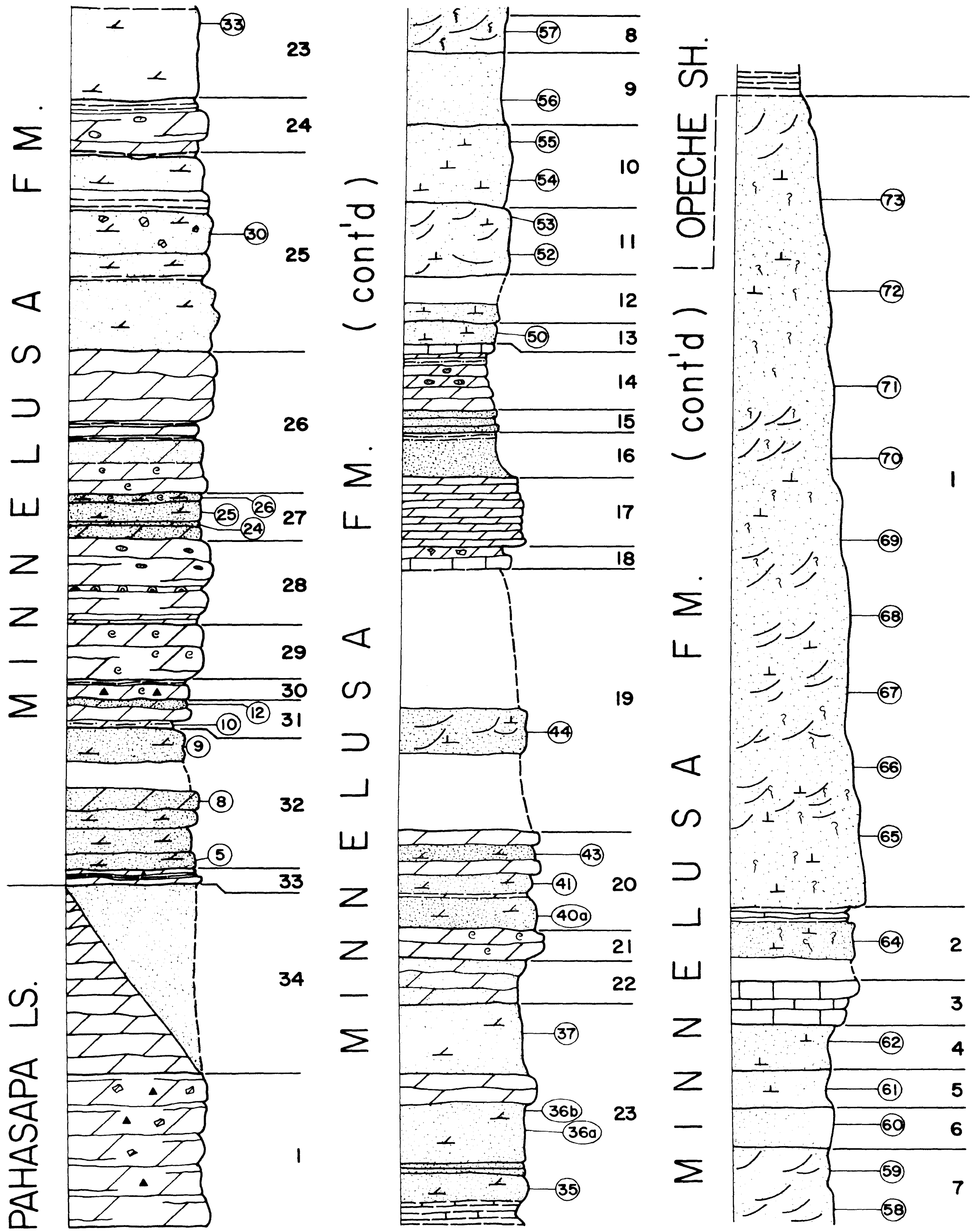

Figure 23. Boulder Canyon Section

3. BOULDER CANYON SECTION

Measured in Boulder Creek Canyon 8 miles east of Deadwood, Sec. 13, T.5 N., R.4 E, Lawrence Co., S. Dakota. Measured with rule and hand level.

Unit No.	Description	Thickness in feet
	Opeche Formation (Permian):	
	Shale red, sandy and sandstone, red, mostly covered	Not measured
	Minnelusa Formation (Permo-Pennsylvanian)	
1.	Sandstone, siliceous, calcareous to non-calcareous, siliceous; gray to white; fine-grained; hard; cross-bedded with SW dips; massive, cliff-forming	107.8
2.	Sandstone, calcareous, siliceous, buff, fine-grained, knobby-weathering, siliceous but friable, 2.4 foot limestone and red shale at top (red marker bed); covered at bottom	9.2
3.	Limestone, light gray, thick-bedded, laminated, middle part soft	5.4
4.	Sandstone, silty, calcareous, reddish, fine-grained, partly covered	6.2
5.	Sandstone, slightly calcareous, silty, buff, very fine-grained, knobby weathering	5.0
6.	Sandstone, non-calcareous, pink fine-grained, with fracture-filling pattern	5.0
7.	Sandstone, non-calcareous, silty, pinkish brown, very fine-grained, cross-bedded with SW dips	10.0
8.	Sandstone, siliceous, pink, fine-grained, laminated, massive, cross-bedded with SW dips	5.0
9.	Sandstone, non-calcareous, pinkish brown, very fine-grained, massive, friable, black spots	9.5
10.	Sandstone, slightly calcareous, creamy white to buff very fine-grained, massive, friable	10.0
11.	Sandstone, slightly calcareous, (7% $CaCO_3$), yellowish brown, very fine-grained, friable, knobby-weathering, massive, cross-bedded with SW dips	10.0

12.	Sandstone, calcareous, pale red, soft, very fine-grained, mostly covered; lower 2 feet hard with possible burrows....................................	5.5
13.	Sandstone, calcareous, silty, yellowish brown, very fine-grained, massive with small ferruginous concretions..	3.3
14.	Dolomite, very light gray, fine-grained, wavy-bedded, with vugs (1-4") lined with calcite, thin- to medium-bedded; 0.4 feet red, soft sandstone 2 feet from top...	8.4
15.	Sandstone and claystone, light pinkish, gray..............	3.0
16.	Sandstone, light yellowish buff, very fine-grained, upper 1.3 feet is red............................	4.6
17.	Dolomite, light gray with brick red streaks, thin-bedded (0.1-0.2 feet), generally laminated, small, calcareous, scalenohedron-lined cavities, ledge forming..	10.7
18.	Limestone, gray, fine-grained, brecciated, brick red at top, mottling on surface..........................	2.0
19.	Sandstone, silty, calcareous, yellowish brown, grades into purple with red clay patches, massive, cross-bedded, mostly covered.............................	34.1
20.	Sandstone, dolomitic; lower beds silty, pink; very fine-grained; thick to massive, well indurated; inter-bedded with shale and dolomite. Lowest beds heavily stained with limonite cement and contain irregular claystone laminations.................................	12.8
21.	Limestone, light gray, fine-grained, vuggy, thick-bedded, with marine fossils (crinoids, bryozoans).........	4.5
22.	Sandstone, very dolomitic, pink with brown spots (limonite), very fine-grained; well indurated.............	5.6
23.	Sandstone, dolomitic, silty at top, pale red, very fine-grained, thick- to massive-bedded, moderately indurated, knobby-weathering near top; interbedded with shale and dolomite......................	41.4
24.	Dolomite, gray, fine-grained, thick to massive, brittle, with shale at top and bottom...................	8.5

25. Sandstone, dolomitic, gray, very fine-grained, massive; interbedded with shale; brecciated and slickensided near top.................................... 26.2

26. Dolomite, gray to pink, fine-grained, massive, brittle, interbedded with shale, sandy near bottom. Lowest beds contain fossil molds......................... 19.5

27. Sandstone, dolomitic, very dolomitic at top and bottom (47% $MgCO_3$, 47% sand, and 6% silt and clay): pink; very fine-grained; medium to thick-bedded; well-indurated; contain fossil molds at top. Iron oxide cement at bottom................................. 5.4

28. Dolomite, gray to pink, massive, vuggy, brittle at top; contains stromatolites (?)................ 11.7

29. Dolomite, gray, very fossiliferous (molds), massive, no distinctive beds, bittle...................... 7.7

30. Dolomite, gray, fine-grained, brittle, cherty. Contains molds and secondary limonite masses Shale at top.. 2.3

31. Dolomite, gray, thick bedded, arenaceous at top with ferruginous fracture fillings; sandy, argillaceous, pink at bottom with small limonitic masses................ 3.8

32. Sandstone, dolomitic at top and bottom; arenaceous dolomite in the middle; silty, pink, very fine-grained, thick to massive bedded, very well indurated, ledge-forming.. 19.0

33. Dolomite, gray to purple, cherty at top, medium-bedded; interbedded with bright red shale................. 1.70

34. Talus, consists of white clayey sandstone................. 20.25

Total thickness of Minnelusa Fm...................445.00

Pahasapa Limestone (Mississippian)

1. Dolomite, gray cherty, massive, brecciated.......Not measured

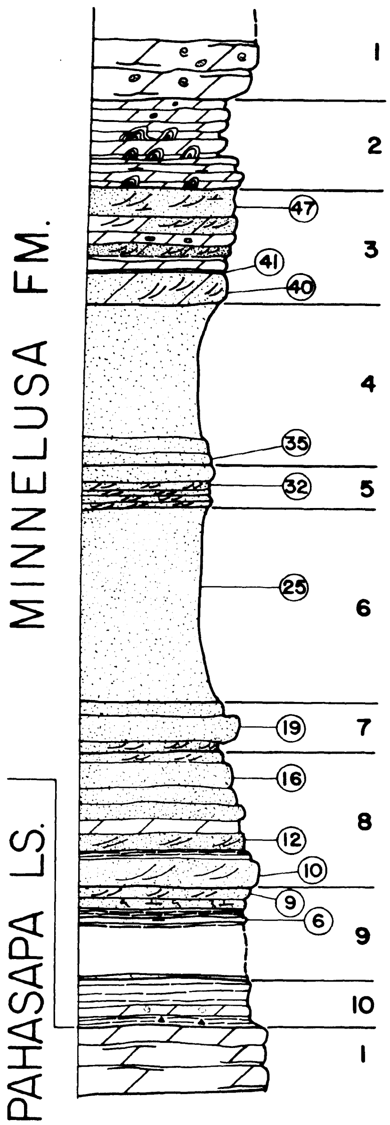

Figure 24. Boulder Creek section (lower portion only)

4. BOULDER CREEK SECTION

Measured in Boulder Creek Canyon, Sec. 23, T. 5 N., R.4 E., Lawrence Co., S. Dakota, Measured with rule and hand level.

Unit No.	Description	Thickness in feet
	Lower portion and the limestone of the middle portion (Desmoinesian)	
1.	Dolomite, light gray, fine-grained, granular, massive with vugs filled with calcite, very fossiliferous	6.7
2.	Dolomite, gray, fine-grained, granular, thick-bedded; contains vugs lined with calcite; interbedded with algal laminations (LLH type); arenaceous near bottom	3.4
3.	Sandstone, dolomitic, and arenaceous dolomite, pinkish gray, cross-bedded, interbedded with thin- to medium-bedded dolomite, gray, granular with calcite vugs and limonite nodules	12.0
4.	Sandstone of various shades of brick red, purple and yellow, with possible gypsiferous cement; argillaceous; very hard; exposed in creek bed	17.7
5.	Sandstone, white, friable, cross-bedding	5.0
6.	Sandstone, white, very fine-grained, loose	21.1
7.	Sandstone, white, very fine-grained, friable to loose cross-bedded at bottom	5.5
8.	Sandstone, white, very fine-grained, medium- to thick-bedded, cross-bedded; at top and bottom moderately hard with iron oxide cement; interbedded with dolomite and lenticular shale	14.4
9.	Quartzite composed of very fine-grained sandstone with rounded larger grains; calcareous, pinkish-gray, medium-bedded; interbedded with dark, lenticular, siliceous shale, lower part covered	8.7
10.	Shale, reddish brown, lenticular, siliceous; 1.1 feet dolomite, gray, hard; 1 foot shale and clay, yellowish gray, soft, with residual chert at bottom	5.1
	Pahasapa Limestone (Mississippian)	
1.	Dolomite, fine-grained, dense, hard, uneven bedding	7.0

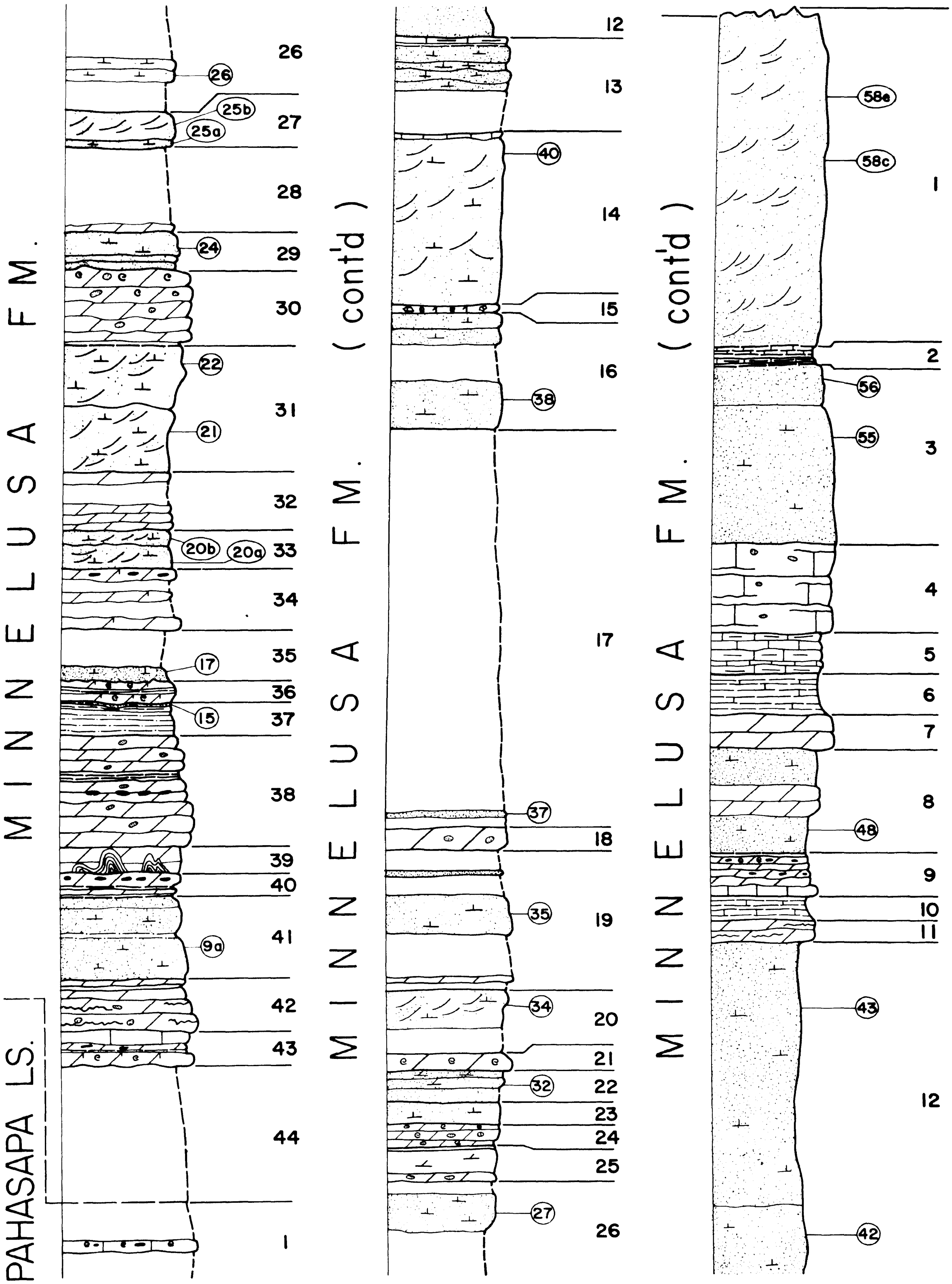

Figure 25. Rapid Canyon Section

5. RAPID CANYON SECTION

Measured in Rapid Creek Canyon, Sec. 8, T. 1 N., R. 7 E, Pennington Co., S. Dakota, near the state fish hatchery, near the city limits.

Unit No.	Description	Thickness in feet
	Opeche Formation (Permian)	
	Shale, red, sandy, and sandstone, red, mostly covered	Not measured
	Minnelusa Formation (Permo-Pennsylvanian)	
1.	Sandstone, calcareous to non-calcareous; gray to buff; fine-grained with coarser, rounded grains; massive, cliff-forming; friable with ferruginous concretions	44.9
2.	Shale, calcareous, red, and limestone, argillaceous, red in the middle (this might be what is known as the red marker, supposed to mark the base of the Permian)	2.4
3.	Sandstone, calcareous to non-calcareous at top, salmon-colored; stained brown due to iron oxide; fine-grained, massive but friable; cliff-forming	24.3
4.	Limestone, argillaceous, calcareous, dark gray, finely crystalline, massive, laminated, with chert lenses and geodes filled with calcite	12.1
5.	Alternating beds of limestone and very argillaceous limestone, purple, knobby-weathering	5.7
6.	Shale, calcareous, purple, nodular	5.5
7.	Limestone, sandy, pink, thick- to massive-bedded with quartz geodes	4.5
8.	Sandstone, calcareous, brick-red, fine-grained, massive; with 4.1 feet dolomite, gray, slabby, in the middle	14.5
9.	Dolomite, pink, medium- to thick-bedded; contains chert nodules; upper part contains fossil molds. Shale at top	5.5
10.	Shale, calcareous, red, nodular	3.0
11.	Dolomite, pink, sandy, argillaceous, stylolitic	3.0

12. Sandstone, calcareous, white to gray, fine-grained, massive, cliff-forming, cavernous, brecciated..49.3

13. Sandstone, very calcareous, with irregular, wavy bedding (bedding dies out laterally), and limestone, argillaceous, at top.........................13.4

14. Sandstone, calcareous, buff, very fine-grained, cross-bedded; the upper part very calcareous. Limestone bed at top..................................22.9

15. Limestone, dolomitic, with fossil molds; brecciated at top......................................1.0

16. Sandstone, calcareous, silty, red, very fine-grained, friable, massive, partly covered................15.7

17. Covered..43.5

18. Dolomite, sandy, light gray with pink streaks, thick- and wavy-bedded, vuggy...........................3.0

19. Sandstone, calcareous; salmon-red, cross-bedded; mostly covered, and dolomite, gray, pink-mottled, at bottom...19.0

20. Sandstone, slightly calcareous, silty, salmon red, cross-bedded with SW dips...............................8.5

21. Dolomite, pink, brittle, ledge-forming, thick-bedded. Contains fossil molds..........................1.9

22. Sandstone, dolomitic, purple, very fine-grained; medium-bedded with irregular siltstone laminations; partly covered...4.4

23. Sandstone, calcareous, purplish gray. Contains fragments of limestone which decrease upward.............3.0

24. Dolomite, pinkish gray, thick-bedded in the middle and thin-bedded at top and bottom. Contains casts of fossils, (brachipods, crinoids)................3.0

25. Sandstone, dolomitic, creamy white, very fine-grained and limestone, dark gray, vuggy, at bottom.......4.2

26. Sandstone, calcareous, white, very fine-grained, thick-bedded to massive, friable, knobby-weathering, mostly covered...26.8

27. Sandstone, non-calcareous, pink, massive, cross-bedded, friable; calcareous, white, medium-bedded, knobby-weathering at bottom............................4.6

28. Dolomite, medium-bedded, mostly covered..................11.6

29. Sandstone, calcareous, fine-grained, lower part is buff, thin- and wavy-bedded, hard; upper part massive; has calcite streaks.............................4.8

30. Limestone, gray to tan, with medium, undulatory bedding, contains chert nodules and vugs filled with calcite; fossil molds at top; lower part is covered...10.0

31. Sandstone, calcareous, white, very fine-grained, massive, cross-bedded with NW-SE dips; stained yellowish brown due to iron oxides; hard; shale at top. Weathered surface is knobby.......................17.2

32. Dolomite, medium-bedded, partly covered..................8.0

33. Sandstone, calcareous, white, very fine-grained, thick-bedded, cross-bedded...............................4.8

34. Dolomite, calcareous, gray, finely crystalline, thick-bedded, partly covered; upper part contains chert nodules..8.5

35. Sandstone, white, mostly covered, erosional unconformity at top...7.0

36. Dolomite, pinkish gray, medium-bedded, with fossil molds and vugs filled with calcite......................3.0

37. Siltstone, micaceous, dark gray, thin- to medium-bedded...4.5

38. Dolomite, gray, dense, slabby, medium- to thick-bedded contains chert nodules and coarse, spar-filled vugs; laminated near top; interbedded with gray, lenticular shale..15.3

39. Dolomite with algal laminations.........................3.2

40. Limestone, dolomitic, light gray, fine-grained, medium- to thick-bedded, cherty, interbedded with shale..3.2

41. Sandstone, calcareous, grayish pink, very fine-grained, massive; weathers into ledges; interbedded with siltstone..11.3

42. Dolomite, dark gray, finely crystalline, thick-bedded, stylolitic. Medium-bedded, vuggy. Contains fossil molds (brachipods) at bottom....................6.5

43. Limestone and dolomitic limestone; gray; finely crystalline; medium- to thick-bedded; sandy, with chert nodules. Cherty in the middle...............4.6

44. Covered..18.0

Total thickness of Minnelusa Fm...................491

Pahasapa Limestone (Mississippian)

1. Covered; one fossiliferous bed exposed containing brachipods and crinoid stem fragments and chert nodules......................................10.0

APPENDIX B

Grain Size Parameters Data

Sample No.	Mean Size M_z	Standard Deviation (Inman)	Skewness (Inman)	Kurtosis (Folk & Ward)
A-5	3.48	0.17	0.35	--*
A-8	3.31	0.36	-0.17	--
A-24	3.40	0.55	0.00	--
A-25	3.42	0.17	0.14	--
A-26	3.38	0.25	-0.10	--
A-30	3.28	0.40	-0.25	--
A-33	3.08	0.47	-0.05	--
A-35	3.06	0.59	0.02	--
A-36a	3.32	0.38	-0.13	--
A-36b	3.09	0.54	-0.30	--
A-37	3.22	0.53	-0.24	--
A-43	3.28	0.40	-0.25	--
A-44	3.50	0.33	-0.00	--
A-52	3.23	0.36	-0.17	--
A-53	3.05	0.44	-0.09	1.26
A-54	3.10	0.36	-0.10	0.99
A-55	3.06	0.36	0.03	1.12
A-56	3.01	0.38	0.13	1.02
A-57	2.75	0.70	-0.21	0.75
A-58	3.23	0.34	-0.19	--
A-59	3.32	0.46	0.08	--
A-60	2.97	0.38	0.07	1.06
A-61	3.08	0.45	0.11	--
A-62	2.98	0.54	0.16	--
A-64	2.97	0.45	0.06	1.23
A-65	2.64	0.74	0.19	--
A-66	3.01	0.38	0.13	1.27
A-67	2.69	0.56	-0.02	0.83
A-68	3.02	0.38	0.20	1.16
A-69	2.48	0.34	-0.19	0.97
A-70	2.70	0.46	-0.08	0.99
A-72	2.76	0.46	0.03	1.19
A-73	2.54	0.44	-0.03	0.90
B-2	3.23	0.29	-0.22	--
B-15a	3.32	0.61	0.35	--
B-18	3.02	0.40	0.19	1.26
B-22	3.26	0.34	-0.19	0.98
B-23	3.12	0.34	-0.04	1.32
B-24	3.27	0.34	-0.26	--

* Not calculated

Sample No.	Mean Size M_z	Standard Deviation (Inman)	Skewness (Inman)	Kurtosis (Folk & Ward)
B-25	3.28	0.29	-0.22	--
B-26	3.12	0.34	-0.04	1.36
B-27a	3.09	0.39	0.16	--
B-27c	3.07	0.35	0.21	1.23
B-28	2.71	0.54	0.02	0.88
B-30	3.16	0.46	-0.30	--
B-31	2.78	0.55	-0.05	1.07
B-32	2.97	0.46	0.24	--
B-38	2.82	0.64	-0.14	0.78
B-43	3.11	0.43	-0.24	--
B-44	3.32	0.50	-0.15	--
B-45	3.01	0.39	0.03	1.08
B-51	3.29	0.32	-0.15	--
B-52	3.23	0.31	-0.20	--
B-53	2.92	0.49	-0.08	0.97
B-55	3.06	0.44	0.03	--
B-59a	3.42	0.35	0.21	--
B-59b	3.18	0.44	-0.31	--
B-60	3.38	0.44	0.20	--
B-63	3.12	0.39	-0.10	--
B-64	2.67	0.45	0.17	0.97
B-65	2.68	0.42	-0.06	1.28
B-66	3.15	0.35	0.21	--
B-67	2.85	0.40	0.19	--
C-15	3.36	0.20	-0.13	--
C-23	3.30	0.35	0.00	--
C-25	3.39	0.64	0.33	--
C-28	3.18	0.39	0.03	--
C-41	3.42	0.54	-0.02	--
C-42	3.31	0.28	-0.09	--
C-43a	3.32	0.29	-0.13	--
C-45	3.01	0.49	0.03	--
C-46	3.01	0.49	0.03	1.14
C-47a	2.92	0.50	0.20	1.24
C-47b	2.94	0.39	0.55	1.02
C-47c	2.87	0.40	0.38	1.02
C-47d	2.59	0.47	-0.11	1.02
C-49	3.33	0.28	-0.09	--
C-50	2.89	0.51	0.12	1.08
C-51	2.83	0.36	0.45	--
C-53	2.89	0.41	0.15	1.06
D-9	3.51	0.46	0.19	--
D-17	3.42	0.57	0.26	--
D-24	3.83	0.68	0.07	--
D-27	3.14	0.35	0.07	--
D-35	3.42	0.47	0.00	--

Sample No.	Mean Size M_z	Standard Deviation (Inman)	Skewness (Inman)	Kurtosis (Folk & Ward)
D-38	3.30	0.50	0.00	--
D-40	3.01	0.39	0.23	--
D-42	2.65	0.65	0.00	0.96
D-58	2.49	0.63	0.64	1.18
E-10	2.82	0.68	0.00	--
E-16	3.17	0.49	-0.23	--
E-19	2.17	0.64	0.53	1.41
E-25	3.04	0.38	0.27	--
E-40	3.41	0.28	0.18	--

APPENDIX C

Sorting and Skewness for 37 Samples Calculated by the Graphic Measures of Folk and Ward (1957)

Sample No.	Inclusive Standard Deviation (Folk)	Skewness (Folk & Ward)
A-52b	0.51	-0.02
A-53	0.38	-0.02
A-55	0.41	0.02
A-56	0.40	0.06
A-57	0.67	-0.13
A-60	0.40	-0.01
A-64	0.52	0.10
A-66	0.42	0.02
A-67	0.52	0.03
A-68	0.43	0.26
A-69	0.37	-0.03
A-70	0.45	0.03
A-72	0.44	0.08
A-73	0.43	0.06
B-18	0.48	0.17
B-23	0.35	0.00
B-24	0.40	-0.07
B-26	0.41	0.08
B-27c	0.41	0.27
B-28	0.50	0.03
B-31	0.52	-0.03
B-38	0.61	-0.16
B-45	0.41	-0.00
B-53	0.49	-0.09
B-64	0.42	0.22
B-65	0.42	0.04
C-45	0.53	0.05
C-46	0.57	0.08
C-47b	0.40	0.56
C-47c	0.39	0.41
C-47d	0.47	-0.02
C-50	0.54	0.10
C-53	0.42	0.10
C-61	0.55	-0.02
D-40	0.41	0.22
D-17	0.61	0.63
E-19	0.62	0.52

APPENDIX D

Carbonate Cement and Silt and Clay Ratio

Sample No.	$CaCO_3$ Percent	Silt and Clay Percent of the Sand*
A-5	34.20	10.57
A-8	50	10.58
A-9	28.86	18.12
A-10	54.89	56.79
A-12	55.59	19.27
A-24	47.69	15.85
A-25	22.23	5.82
A-26	40.52	7.01
A-30	29.31	8.19
A-33	7.5	8.35
A-35	21	10.06
A-36a	5.25	10.21
A-36b	25	7.21
A-37	13.8	11.74
A-40	22	20.64
A-41	16.94	36.11
A-43	14.8	7.78
A-44	14.16	13.24
A-50	30	13.16
A-52	7.7	8.34
A-53	7.1	5.93
A-54	5.6	4.51
A-55	4.4	3.77
A-56	0	3.13
A-57	0	4.98
A-58	2.5	9.67
A-59	0	14.51
A-60	0	3.91
A-61	7.5	11.79
A-62	37.6	12.06
A-64	11	5.46
A-65	24	7.48
A-66	18	4.48
A-67	1.3	3.57
A-68	24	5.29
A-69	0	1.31
A-70	24.2	4.03
A-71	17.6	3.88
A-72	14	1.55
A-73	0	--

* Ratio of the pan fraction to the sand fraction

Sample No.	$CaCO_3$ Percent	Silt & Clay Percent of the Sand
B-5	60.8	38.72
B-7	36.59	31.44
B-15a	48.2	16.10
B-15b	53.4	78.02
B-18	34	5.26
B-22	37.93	11.53
B-23	28.5	4.33
B-24	29.9	6.69
B-25	19.74	7.5
B-26	6.2	5.42
B-27a	14.9	6.74
B-27c	18.8	5.74
B-28	0	2.23
B-30	0	7.25
B-31	0	3.09
B-32	0	8.40
B-38	31	2.48
B-43	22	8.67
B-44	3.2	15.18
B-45	19.6	3.92
B-51	23.5	3.92
B-52	17.5	7.04
B-53	14	3.63
B-55	14.6	7.82
B-59a	28.1	14.98
B-59b	18	10.77
B-60	28.8	15.72
B-61	0	--*
B-62	0	18.62
B-63	0	10.23
B-64	0	2.21
B-65	20.30	3.72
B-66	0	12.03
B-67	0	6.36
C-15	37.1	7.86
C-16	68.6	--
C-23	40.40	10.04
C-24	57.3	49.49
C-25	29.1	16.62
C-27	8.4	--
C-28	49.0	12.10
C-29	29.29	--

* The sample was not sieved

Sample No.	$CaCO_3$ Percent	Silt & Clay Percent of the Sand
C-30	52	--
C-38	4	23.51
C-41	31	15.87
C-42	14	9.27
C-43a	13	8.6
C-45	7	5.06
C-46	7.5	6.17
C-47a	11	6.33
C-47c	6	3.20
C-47d	3.6	1.58
C-49	13	8.17
C-50	6.4	4.88
C-51	25.5	6.67
C-52	28	20.27
C-53	15	2.03
C-58	25	13.72
C-59	23	--
C-61	17.5	3.91
D-9	31.5	15.98
D-15	13.5	--
D-17	38.5	5.65
D-20a	22.1	--
D-20b	14.5	--
D-21	36.0	--
D-22	21.30	--
D-24	22	11.89
D-25a	29.3	--
D-25b	0	--
D-26	27.1	--
D-27	27.6	6.73
D-32	32	--
D-34	0	--
D-35	28	14.68
D-37	22.2	--
D-38	26.7	15.31
D-40	26.0	4.32
D-42	38.30	7.05
D-43	26.7	--
D-55	8.0	--
D-56	2.3	--
D-58c	3.0	4.7
D-58e	0.0	--

Sample No.	$CaCO_3$ Percent	Silt & Clay Percent of the Sand
E-6	0	--
E-9	0	--
E-10	0	--
E-16	0	--
E-19	0	--
E-25	0	--
E-32	0	--
E-35	0	--
E-40	58	--
E-41	--	--
E-47	--	28
E-50	--	--